

**Assessing the Impacts of Urbanization  
on Shellfish Growing Areas in Puget Sound**

**Final Report**

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## LIST OF ACRONYMS

AI	Aggregation Index
DEM	Digital Elevation Model
GIS	Geographical Information System
MPS	Mean Patch Size
NSSP	National Shellfish Sanitation Program
PLANDJ	Percent Land Adjacency
PRISM	Puget Sound Regional Synthesis Model, University of Washington
PSAT	Puget Sound Action Team
$r$	Pearson product-moment correlation coefficient
$R^2$	R Squared correlation coefficient of determination
SRSS	Systematic Random Sampling Survey
TIA	Total Impervious Area
TIGER	Topographically Integrated Geographic Encoding and Referencing
UERL	Urban Ecology Research Laboratory, University of Washington
USGS	United States Geologic Survey
VIF	Value Inflation Factor
WAGDA	Washington Geographic Data Alliance
WDOH	Washington Department of Health

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## EXECUTIVE SUMMARY

This study explored the relationship between landscape patterns and nearshore water quality in shellfish growing areas of Puget Sound. We developed an empirical analysis of 32 basins selected to represent a gradient of urban land use/land cover patterns. Using bacterial contamination as an indicator of nearshore conditions, we developed a cross-sectional analysis across the 32 basins to assess what landscape factors best explain water quality conditions in Puget Sound's shellfish growing areas. Our hypothesis was that variations in land cover composition, landscape configuration, land use intensity, and connectivity explain most of the variation in nearshore water quality conditions.

The study is based on a landscape analysis approach. By combining remotely sensed data with land use and demographic data, we applied a set of landscape metrics developed in landscape ecology to quantify human settlement patterns, both in its composition and configuration of built elements and land uses on the landscape. Two scales of analysis were applied to assess influence of variables at the basin and local scale. A selection of variables was considered, including human population density, road density, percent land use, amount of impervious cover, aggregation of paved land, and amount and fragmentation of forest cover. Remote sensing and geographic information systems (GIS) have proven to be powerful landscape analysis tools, but the interpretation and analysis of the relationships between urban landscapes and nearshore environments present unique challenges, most notably gaps in important data sets and the complications inherent in sharing scientific data across disciplines and political boundaries.

The study shows that measurable differences in nearshore water quality can be detected across Puget Sound in watersheds with different amounts and fragmentation of forest cover at the basin scale (18 Puget Sound sites). Among the most urbanized basins (12 Puget Sound sites) the difference in water quality is associated with the amount and aggregation of impervious surface. While the amount of impervious area in the basins provides an effective measure of human impacts on nearshore water quality, variables measuring its spatial configuration (i.e., aggregation of paved land) and connectivity (i.e., total length of roads) show that the relationship between urbanization and water quality is not a linear one.

Land use and wastewater infrastructure are suspected to influence the impact of increasing human population on coastal environments. In order to explore this relationship further, additional data is required to research the interactions. The existing data that describe land use and infrastructure variables were limited and need to be improved to test hypotheses on the role that these factors play in mediating effects of urbanization on nearshore environments.

## I. RESEARCH SCOPE AND OBJECTIVES

The health of the Puget Sound estuary is vital to many economic, cultural, and recreational activities. Its waters provide habitat and feeding grounds for fish and shellfish, prized icons of the Pacific Northwest. While much of Puget Sound is still healthy, rapid landscape change associated with population growth and urbanization within nearshore environments and adjacent watersheds is degrading water quality, resulting in increased closures of fishing, recreation activities, and shellfish harvesting (PSAT, 2002). A steady loss of habitat, decline in some fish and wildlife populations, and closures of shellfish beds are signs that the Puget Sound is threatened. These trends are likely to continue over the next several decades with increasing population growth and conversion of forested land to suburban development (Vitousek et al. 1997). Puget Sound's population increased by 17% between 1991 and 2002 to 4 million people and is expected to exceed five million by 2020 (Glasoe and Christy, 2004).

### 1.1 Research Objectives

Effects of land cover change on aquatic ecosystems have been extensively studied (e.g., Omernick 1987, Roth et al. 1996, May et al. 1997, Paul and Mayer 2001). These studies link increases in degradation of water quality with increases in human population density and amount of impervious cover (e.g., roofs, roads, parking lots). Human population growth and land cover change in coastal areas increase the sources of anthropogenic-induced pollution, microbial pathogens and potential risks of human exposure to contaminants. Urbanization is one of the key drivers of land transformation and causes the most persistent change through vegetation clearing, compacting soil, artificially draining surface water, and covering the land surface with impervious cover. Impervious surface is a well-documented indicator of the consequences land development has on the ecological integrity of aquatic ecosystems. Although many previous studies have addressed the relationship between watershed urbanization and the associated biotic conditions in streams (Karr and Schlosser 1978, Arnold and Gibbons 1996, Booth et al. 2002) and coastal areas (Fulton et al. 1993), few have investigated how the *patterns* of urbanization and forest cover control hydrological, geomorphological, and ecological processes in human-dominated watersheds. We do not know, for example, how clustered versus dispersed urban patterns affect nearshore ecological conditions.

Two main objectives informed this study:

- To study, test and quantify the relationship between urban development and its impacts on shellfish growing areas in Puget Sound using appropriate environmental indicators of nearshore conditions. Measures of urban development included landscape patterns (composition and configuration) and land use intensity. Bacterial contamination served as the primary environmental indicator and measure of shoreline conditions for shellfish harvesting.
- Within the limits set by the available data, to develop an empirical analysis to assess nearshore water quality conditions under specific build out scenarios. This analytical approach was used to identify critical landscape conditions required to preserve water quality in shellfish growing areas under increasing development pressure.

## 1.2 Research Hypotheses

We built on previous research studying the impact of land use on nearshore environments (Griffin et al. 1999, Holland et al. 2004, Lipp et al. 2001a, Lipp et al. 2001b, Mallin et al. 2001, White et al. 2000 White et al. 2000) to generate and test formal hypotheses on the relationships between landscape patterns and shellfish growing areas conditions in the Puget Sound region. We focused on two questions:

- How do variables affecting shellfish growing areas vary on an urban gradient?
- What pattern metrics best predict water quality in nearshore environments that meet shellfish harvesting standards?

We hypothesized that the stressors of nearshore environments across Puget Sound bays can be described along distinct patterns of land use and land cover at multiple spatial scales. Specifically we defined two hypotheses:

1. Nearshore conditions can be differentiated across a gradient of dispersed versus clustered impervious surfaces and/or forest patches within a drainage basin.
2. The predictive ability of models that relate landscape pattern to nearshore conditions can be improved by including the type and intensity of land use.

### 1.3 Urban Ecology Approach

Our project applies an *urban ecology* approach to the study of human-environment dynamics (Pickett et al. 2001, Grimm et al. 2001, Alberti et al. 2003). Urban ecology seeks to understand how human and biophysical processes interact over time and space. The spatial relationships of elements within the landscape serve as a fundamental focus of analysis. To simulate and assess the impact of alternative development scenarios on shellfish growing areas, our project analyzes the interactions between landscape patterns (land use and land cover) and ecological conditions in the growing areas (bacterial contamination). We apply metrics of landscape patterns that we hypothesize to be linked to ecological processes in urbanizing landscapes. We build upon existing established scientific understanding of the relationships between hydrologic, geomorphic, and biological conditions, and new empirical findings developed to assess the effects of spatial and temporal patterns of human activities on aquatic ecosystems. The analysis is based upon the assessment of these effects within the landscape context using geographical information system technology and remotely-sensed data.

## II. STUDY METHODS

We addressed the dimensions of our research questions across space and time as cross-sectional and longitudinal analyses, respectively. Cross-sectional analyses compare different watersheds to each other at one point in time. Longitudinal analyses compare how different watersheds change over time. First we identified, characterized, and quantified landscape patterns in selected areas using a set of landscape metrics. We delineated the drainage area of the coastal area using United States Geological Survey (USGS) 10-m or 30-m Digital Elevation Model for the Puget Sound

region. We selected study sites using three levels of criteria. We summarized bacterial contamination levels at each site using several statistical metrics. We used historical land use and land cover data to represent landscape characteristics. We measured landscape patterns using selected spatial metrics of landscape composition and configuration that we previously found to be relevant to ecological processes in urbanizing landscapes. We used a range of multivariate techniques to establish empirical relationships between metrics of landscape patterns and a series of stressors of nearshore ecosystems in selected bays. Finally, we looked for incremental predictive power by adding the variables describing land use patterns and intensity.

Data limitations, in terms of both their availability and quality, have imposed a number of restrictions on the study design and implementation. While historical data for fecal coliform bacteria were available from 1988 through 2002, historical land cover data were not available for the entire Puget Sound region. Furthermore there were significant inconsistencies among the available fecal coliform data with respect to their historical length and breadth across the different stations. This has impeded to conduct a fully longitudinal study and required to devise a strategy to process the fecal coliform data as described below.

## 2.1 Study Area and Scales of Analysis

Puget Sound is an estuary characterized by a series of underwater valleys and ridges fed by more than 10,000 streams and rivers. Puget Sound's watersheds are predominantly covered by forest, and timber harvest is the dominant land use activity. The mainstem rivers that drain this landscape extend from the rugged unpopulated crests of the Cascade Range and Olympic Mountains down to the rapidly urbanizing lowlands of Puget Sound. They display a 100+ year legacy dominated by forest practices and floodplain alteration, which in most cases has included channelizing, diking, draining, and filling. Many of the tributary streams and smaller sub-basins, however, are fully contained within the gentle topography of the Puget lowlands. Over the last century these lowlands have been subjected first to logging, then agriculture, and now increasingly to urban development. In a majority of these areas, suburban and urban development is now the dominant land use.

## Site Selection

In coordination with Washington Department of Health (DOH) and Puget Sound Action Team (PSAT), we selected 32 potential study sites based on the availability of accurate and comprehensive water quality data (Figure 1, Table 1). Of the original 32 candidate areas, 15 sites were used as a preliminary test case to select the most appropriate landscape metrics for the study objectives. The overall study was based primarily on a comparative or cross-sectional analysis representing different patterns of urban development in 11 counties, including lands owned by public, private, tribal, and military entities (Figure 2, Figure 3). Cross-sectional sites were selected to represent a gradient of urban land use/land cover composition, configuration, and intensity. A comparison across time, or longitudinal land cover analysis, was explored exclusively in Puget Sound sites where historical land cover data were available. Longitudinal sites were also selected to represent different degrees of urban growth and land cover change from 1991 and 1999 within the Puget Sound region. The longitudinal comparison did not include historical water quality data due to the lack of data for all 12 sites. After compiling and evaluating the available data, we selected study sites that satisfied the following list of criteria<sup>1</sup>. A complete list of candidate sites, cross-sectional sites and longitudinal land cover subset are provided in Figures 1 and 2.

### Criteria for Site Selection:

#### Candidate sites: 32 sites distributed across Puget Sound

- smaller watersheds (comparatively within the region)
- relatively distinctive or homogeneous land use present within the drainage
- ideally, enclosed embayment (preferred to open beaches which are more exposed to mixing and tidal current affects)

#### Cross-sectional study: 18 sites of 32 candidate sites

- historical water quality data for 1998-2002

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<sup>1</sup>The majority of the excluded candidate sites were disqualified due to the lack of available water quality data. Additionally, we eliminated: Portage Bay due to the influences of the large river system that was not captured within 1500 meters of the water quality stations; Drayton Harbor due to the confounding influence of agriculture within the basin.

- representative sample of development (from urban to rural)
- geographic distribution to represent the Puget Sound region

Longitudinal land cover subset: 12 sites of 18 study sites

- historical land cover data for 1991, 1999 and 2002

## Basin Delineation

We delineated drainage basins for each shellfish growing area to determine the land area contributing to the water quality measurements collected within the 32 bays.<sup>2</sup> DOH supplied the geographic coordinates for the marine water quality monitoring stations in each of the study areas. Figure 4 is an example of the monitoring station locations within Henderson Inlet. These locations defined the embayment area associated with each study site (Figure 5). The definition of a watershed is “an area in which water drains to a common outlet—a point—on a larger stream or body of water.” The “lowest elevation collection points” are referred to as *pour points*. Traditional watershed delineation works from the pour point or “outlet” to determine the upstream area contributing to that point, and it assumes a singular direction of flow (i.e. downstream). In this study, the contributing area included not only streams, but also shoreline surface flow and ground water seeps. Tidal mixing and currents also factored into the water quality of each monitoring station, but data related to currents and tides, both important elements of water quality, were limited and were not available to be explored in depth. Flow direction and flow accumulation were calculated for the entire Puget Sound using geographic information system software (ArcView 3.2 and program extension HYDRO). The shoreline was isolated from the USGS’s digital elevation model (DEM)<sup>3</sup> for the Puget Sound area. Measuring from the water quality stations, the shoreline within each basin was clipped by a 1500-meter cost distance

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<sup>2</sup> We make an important distinction that the boundaries of the study areas were determined to coincide with the water quality stations (1500 meters from any of the bay’s stations). Therefore due to the limits of the water quality data, the study area may not include the entire bay or waterbody such as in the case of Port Townsend. Due to the location of the monitoring stations, Port Townsend is split into two sub-basins in this analysis.

<sup>3</sup> A *digital elevation model* is a grid file where each cell contains an attribute relating to its elevation. This project used a 30 meter DEM supplied by the United States Geological Survey.

(Figure 6)<sup>4</sup>. Within this distance, each shoreline pixel was converted to a pour point. Using the flow direction grid, the WATERSHED command in ARC/INFO GRID was used to complete the delineation process.

## Local Scale Analysis

To assess the local influence of land cover and land use on nearshore environments, we delineated a buffer<sup>5</sup> of 500 meters from the shoreline through the flow path, or following the topography as water would flow through the landscape (Figure 7). We used the flow direction grid to create a distance grid using Arc Info's FLOWLENGTH command<sup>6</sup>. This grid assigned to each pixel the distance (in pixels) that surface runoff needs to travel to reach the shoreline. The 500 meter zone was then used to perform the same analysis of land use and land cover variables conducted at the basin scale.

## 2.2 Data Sources and Variables

Several metrics were selected to measure landscape pattern (Tables 3 and 4). Sub-basin boundaries were determined by using a 30-meter USGS *Digital Elevation Model* (DEM) available from Puget Sound Regional Synthesis Model (PRISM). Historical land cover data for 1991 and 1999 for the central Puget Sound area were available at the Urban Ecology Research Lab (UERL) and were used to measure change in landscape composition and configuration over the eight-year period. For 2002, land cover was interpreted at the UERL from a combination of

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<sup>4</sup> *Clipping* is GIS software terminology for selecting cells from a grid and forming a separate analysis file for a particular purpose determined by the program user. A *cost distance* is a measure of distance between a source cell and a selected target cell. Instead of calculating distance as a straight linear distance, the cost distance is calculated by moving through cells provided as a source grid, in this case water pixels.

<sup>5</sup> A buffer is used here as a zone of specified distance around a selected GIS feature chosen for a particular attribute of a layer of data. Buffering is a technique used in this study to create zones of analysis within a certain distance of the shoreline (for example 500 meters).

<sup>6</sup> A *flow direction grid* is a mathematical calculation that assesses each cell's elevation in relation to its neighboring cell and then assigns the cell a weighted number. From this calculation, the GIS software can determine the direction of water flow across the landscape.

Landsat-TM and Landsat-EMT+ data as part of the PRISM project. Census Data for 1990 and 2000 were obtained from the Washington Geographic Data Alliance (WAGDA). DOH supplied shellfish growing area classifications, monitoring station locations, and water quality data (fecal coliform concentrations). The Puget Sound Regional Council provided transportation data using the U.S. Census TIGER classification system. Eleven counties contributed data describing land use, infrastructure (if existing), and tax assessor data (if available digitally). Additionally, information layers were provided by DOH to supplement missing county data such as the boundaries of national forest, tribal and military lands.

### Land Cover Classification

This study utilized three land cover classification products for the analysis. The land cover products for 1991, 1999, and 2002 were interpreted at the UERL from Landsat Thematic Mapper images of the Puget Sound region. The 1991 and 1999 land cover classifications for the central Puget Sound area were developed for PSAT as part of a landscape change analysis of the Puget lowlands below 500 meters (Alberti et al. 2004). The 2002 land cover, which covers the entire Puget Sound region at all elevations, was produced for PRISM (Alberti et al. 2002).

The 1991 and 1999 land cover data were previously derived from a single USGS Landsat Thematic Mapper <sup>TM</sup> 30-meter resolution image for the central Puget Sound region (Figure 8). The raw Landsat data were preprocessed and corrected for atmosphere and topography. A hybrid classification method was applied to address the spectral heterogeneity of the urban region. This method combines a supervised classification approach with a spectral un-mixing approach. The classification procedure creates a seven-class land cover system, which discriminates between mixed urban and paved urban land cover characterized by different amounts of imperviousness within a 30-meter pixel. Paved Urban is made up of greater than 75% of imperviousness while mixed urban includes between 15% and 75% imperviousness. The remaining land cover classes are forest, grass (which includes shrub and crops), bare soil, clear-cut, and water. An accuracy assessment of the 1991 and 1999 images produced an overall accuracy of 91% and 88% respectively, leading to an overall accuracy of 85% for the land cover change analysis.

For the 2002 land cover analysis, Landsat-TM and Landsat-EMT+ data were acquired for the summer and winter months of 2002 (Figure 9). The data from four images were geo-registered, inter-calibrated, and corrected for various effects of atmosphere and topography to ensure accuracy in land classification. We used a hybrid approach for land cover classification involving supervised classification and spectral unmixing in addition to a seasonal-change analysis for vegetation cover. The supervised classification was used to derive a base land cover image, which included the homogenous classes of paved (dense) urban, mixed urban, clear-cut forest, bare soil, and dry grass. Spectral unmixing was used to a) separate vegetation pixels from non-vegetation and water pixels to aid in the supervised classification process, and b) separate the classes composed of urban and vegetation components into more detailed sub-classes. This approach was useful in areas where landscape features were finer in resolution than the spatial resolution of the satellite instrument and resulting image. Examples of this phenomenon include highly mixed, urban features such as roofs, roads, lawn, trees, driveways and patios. While spectral unmixing of a Landsat pixel cannot reliably identify exact urban materials, it can provide relative proportions of vegetation and urban components, providing a good estimate (or proxy) for urban intensity. In this case, once we identified mixed urban pixels (dense urban and residential urban) using supervised classification, we applied a three-end-member mixing model from which proportions of urban impervious surfaces were derived. We then improved upon the vegetation classes derived from the supervised approach by using the spectral unmixing model and shade-fractions to differentiate between grass and forest cover. Finally, the seasonal change measured between winter and summer data sets was used to improve and disaggregate the vegetation classes. Three data layers were used to improve the accuracy of urban pixels. Using these combined approaches, the final classification for 2002 includes twelve classes: paved urban (>75% impervious); mixed urban (15-75% impervious); grass/shrubs/crops, dry-grass or native grasslands, clear-cut forest, bare soil, forest (combined deciduous and coniferous); snow, rock, or ice; wetlands; shoreline; steep slopes (unclassified) and water (Table 5).

## 2.3 Landscape and Land Use Metrics

For this study, we applied an analysis approach developed within landscape ecology to quantify human settlement patterns in terms of intensity, composition and configuration of built elements and land uses upon the landscape. We selected several metrics, or measurements, of these patterns to compare to the water quality measurements available for each basin.

### Land Use Intensity

Land use intensity metrics include *population density*, *percent of land use* and various metrics of transportation infrastructure. *Population density* for each census block or block section were calculated and then assigned to each of the basins by intersecting, a process of overlaying the census block group coverage with each basin coverage. The census block groups and boundary layers were first projected to Universal Transverse Mercator (UTM) to make them consistent with land cover and other spatial data. Water bodies were used as masks, which is the process of subtracting the area of the water body from the total area of the basin. Population data for census block groups were normalized using the area of the block group that fell within each basin's boundary to determine the total population in the basin. Land use patterns in basins were compiled and quantified by intersecting parcel data obtained from assessor offices to determine percentages of land use types in each basin. The assessor data represents *current* land uses in each basin, as compared to zoning which refers to *potential* future uses. Each county's coding system was calibrated to create a unified system of 13 basic land use codes (Table 6).

Transportation infrastructure metrics were developed by intersecting the TIGER road layer with the basin layer to determine the total lengths of road segments within each basin. *Road density* was calculated by dividing the sum of road lengths by the basin area for four types of roads: local roads, major roads, four-wheel-drive roads, and logging roads (Table 7).

## Landscape Composition and Configuration

We applied several landscape metrics to measure landscape composition and configuration (Table 4). We measured landscape composition by the *percent urban land* as classified in the land cover map. The metrics summarizing the 1991 and 1999 land cover classification refer only to the watershed area below 500 meters due to the classification process. However, the PRISM 2002 land cover classification summarized the entire basin area. The area above that elevation was not included within the land cover classification. We quantified the *percent impervious area* by spectrally unmixing urban land cover pixels. We used FRAGSTATs software to estimate 7 land cover metrics (McGarigal, K. and B.J. Marks, 1995). *Percent land* (Pland) is the sum of the area of all patches of the corresponding patch type divided by total basin area. To measure urban landscape configurations we applied three metrics: *Mean Patch Size* (MPS), the *Aggregation Index* (AI) and *Percentage-of-Like-Adjacency Index* (PLADJ). AI equals the number of similarly classed neighboring pixels (or “like adjacencies”) involving the corresponding class, divided by the maximum possible number of like adjacencies of that class. The PLADJ index is determined as the sum of the number of like adjacencies for each patch type, divided by the total number of cell adjacencies in the landscape, multiplied by 100 (to convert to a percentage). Percentage values were converted prior to analysis using arcsine-square roots.

## 2.4 Water Quality Metrics

Shellfish growing areas are classified by DOH on the basis of comprehensive sanitary surveys involving water quality assessments, pollution source investigations and hydrographic and meteorological evaluations. The surveys and classification system follow the protocols and standards of the National Shellfish Sanitation Program (NSSP). Bacterial contamination, specifically fecal coliform bacteria, is used as the primary measure of water quality because it signals the presence of human or animal feces and, in turn, the possible presence of pathogenic organisms. Due to the historic availability of data, fecal coliform was chosen as the best available indicator at this time. We computed several metrics including geometric mean,

standard deviation, 90<sup>th</sup> percentile, variance of fecal coliform content and number of violations of the DOH standards (Table 8).

## Water Quality Data

The data provided by DOH included all sampling measurements from the Puget Sound area from 1988 through 2002. The current DOH policy uses a systematic random sampling strategy (SRS) when sampling permanent stations (for details, refer to the *Atlas of Fecal Coliform Pollution in Puget Sound: Year 2001*, p. 5). However, there were significant differences in the historic length and breadth of data available for each station and each basin (Figure 10). These differences are attributed to changes in sampling schedules or policies, changes in sampling stations, and funding limitations over time.

Shellfish growing areas are classified on the basis of 30 or more samples per station and a two-part water quality standard: (1) a geometric mean  $\leq 14$  organisms per 100 ml and (2) a 90<sup>th</sup> percentile value  $\leq 43$  organisms per 100 ml (DOH, 2002a). The water quality data set provided by DOH included fecal coliform concentrations, sampling dates, geometric means, 90<sup>th</sup> percentiles, and the Fecal Coliform Pollution Index.

For the purpose of our analysis, we used two approaches to process the fecal coliform data. First we standardized the raw data set to represent all sampling stations equally as described below. Second, we computed statistics with all data values and then compared the results of these two approaches. To standardize the data set, we isolated data during two periods, 1990-1992 and 1998-2002, to correspond with the land cover classifications. Stations without a minimum of 3 samples per season (3 wet-season samples and 3 dry-season samples per year,  $n=6$  per year) were eliminated from the cross-sectional analysis, retaining 18 out of the original 32 study sites. Only seven growing areas had enough stations that qualified for water quality analysis in the time period of the 1990-1992 land cover. Because of the small sample size a longitudinal water quality analysis was not feasible for the entire 1990-2002 period. From each of the stations remaining in the 1998-2002 analysis, a stratified random sample selected to include three

samples per year for each of the two hydrographic seasons (wet season November-March, dry season April-October). The median, geometric mean, standard deviation, 90<sup>th</sup> percentile, variance of fecal coliform content and number of violations of the DOH standard for each station were used as dependant variables in the multivariate regression models. This standardization procedure reduced our sample size to 18 sites across the Puget Sound for the cross-sectional analysis and 12 sites for the longitudinal land cover subset. To understand the impacts of seasonal differences in precipitation, we calculated fecal coliform metrics for both the wet and the dry season separately, and as a combined measure (wet and dry together).

Environmental variables have been shown to have an important influence in explaining part of the variability in fecal coliform across different sites. These include salinity, water temperature, tidal stages, and rainfall (Weiskel et al. 1996, Lipp et al. 2001a, Lipp et al. 2001b, Mallin et al. 2001). However these data were not recorded consistently, were not included in the data set provided by DOH for all stations or measurements in our sample, and therefore were not used in this analysis.

## 2.5 Statistical Analyses

Correlation and regression analyses were performed with SPSS<sup>TM</sup>, a statistical software package, to determine the relationship between measures of water quality (fecal coliform) and the selected landscape metrics. We used the Pearson product-moment correlation coefficient ( $r$ ) to test for associations between land cover measures and fecal coliform. We also used simple regression and multiple regression to explore which factors best explain the variability in fecal coliform density across the bays. We developed a set of apriori models using intensity, composition, and configuration metrics at both the basin and local scales for comparison using an adjusted  $R^2$ . We estimated the value inflation factor (VIF) for each variable to assess collinearity between variables. High VIF values indicate that variables are nearly linear combinations of other variables present in the model, and if included in the model, can reduce the confidence in the parameter estimates for those variables and others (Kleinbaum et al. 1998). We did not include variables with VIF greater than 10 and p-value greater than 0.05.

### III. FINDINGS

Summary statistics of the key variables described in the following sections are presented in Tables 9 through 17. Significant correlations between landscape patterns and fecal coliform are presented in Tables 18 and 19 for the two groups of bays, the Puget Sound cross-sectional sample (n=18) and the longitudinal land cover subset (n= 12). Results of the multi-regression models are presented in Tables 20 and 21.

#### 3.1 Basin Characterization

Most of the candidate drainage basins range in size from about 6 square kilometers in Port Blakely to about 310 square kilometers in Oakland Bay, except a few much larger basins including Samish Bay (378 km<sup>2</sup>), Dungeness Bay (528 km<sup>2</sup>), Budd Inlet (544 km<sup>2</sup>) and Nisqually Reach (2069 km<sup>2</sup>)<sup>7</sup>. *Population density* in the drainage basins ranges from about 3 people per km<sup>2</sup> (Quilcene) to 600 people per km<sup>2</sup> (Henderson Inlet), with most of the basins having densities less than 200 people per km<sup>2</sup> (Figure 11). The basins represent a gradient of urbanization (Figures 12 and 13) ranging from 0.5% *impervious area* in Dabob Bay to 14% in Henderson Inlet (Figure 14)<sup>8</sup>. Conversely, *percent forest* area in the basins vary from 85% in Dabob Bay to 45% in Henderson Inlet. The cross-sectional basins also vary with respect to the degree of land uses within the basins (Figure 15), and for the longitudinal basins, the degree of land cover change that occurred in the eight-year time period for which we had longitudinal land cover data (Figure 16). The measures of *road density* vary between less developed basins such as Dungeness Bay (.63 km/km<sup>2</sup>) and Quilcene Bay (1 km/km<sup>2</sup>) and more developed basins such as East Sound North (4.31 km/km<sup>2</sup>) and Henderson Inlet (4.19 km/km<sup>2</sup>) (Figure 17 and 18). The variability in the level of development across these basins is also reflected in the landscape configuration metrics as measured by the Aggregation Index (AI) for the paved and mixed urban

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<sup>7</sup> The 12 basins within the longitudinal land cover subset range from 13.44 sq.km to 311 sq. km. The larger basins (Budd Inlet, Nisqually Reach, Dungeness Bay, and Samish Bay) are included within 18 study sites. For the land cover metrics, the amount of the larger basins under 500 meters varies, as 84%, 58%, 23%, 89% respectively.

<sup>8</sup> Due to the UERL land cover classification process, land area above 500 meters was not classified. Metrics calculated from land cover, such as *percent forest* and *impervious area*, estimate only the area below 500 meters. The percent of the area in each basin below 500 meters is included in Table 1.

land cover which vary respectively between 15 to 64 (*AI of paved urban*) and between 27 and 68 (*AI of mixed urban*).

### 3.2 Land Use Intensity

*Cross-sectional sample:* Water quality conditions in the 18 bays in Puget Sound were significantly correlated with *population density* particularly during the dry season ( $R = 0.62$ ,  $P < 0.01$ ) and with *road length* ( $R = 0.49$ ,  $P < 0.05$ ) during the wet season. An assessment of land use data across the 18 cross-sectional bays indicated that the available data were not complete or accurate enough to be used for this analysis. We limited the land use analysis to the subset of Puget Sound sites included in the extent of the land cover classifications from 1991 and 1999.

*Longitudinal land cover subset:* When limiting the analysis to the 12 bays in the longitudinal land cover subset, water quality as measured by the wet-season and combined geometric means of fecal coliform was most strongly correlated with *population density* ( $R = 0.72$ ,  $P < 0.01$ ). The metric of *total kilometers of roads* across the basins was also significantly correlated with fecal coliform density in the wet season ( $R=0.76$ ,  $P < 0.01$ ). Also, the data show significant correlations between *percent of multi-family, commercial and industrial land uses* and fecal coliforms in the wet season.

Human *population density* was highly associated with the *amount of impervious cover* using both 1991 ( $R = 0.89$ ,  $P < 0.001$ ) and 2002 ( $R = 0.92$ ,  $P < 0.001$ ), suggesting impervious cover is a good measure of the potential stress that population growth generate for aquatic ecosystems. Population growth was also associated with *road density* ( $R = 0.78$ ,  $P < 0.001$ ), which in turn affects water quality in nearshore environments.

### 3.3 Landscape Composition

*Cross-sectional sample:* Several landscape composition metrics were correlated with water quality conditions as measured by the geometric mean of fecal coliform (Figures 19-20). The best landscape composition predictors of fecal coliform density across all 18 study bays were *percent forest* ( $R=-0.67$ ,  $P < 0.001$ ) and *percent impervious area* ( $R=0.62$ ,  $P<0.01$ ). For the wet season, best land cover composition metrics was *percent impervious* ( $R=-0.56$ ,  $P<0.01$ ).and for dry season percent mixed urban ( $R=0.62$ ,  $P<0.01$ ).

*Longitudinal land cover subset:* When limiting the set of basins to the longitudinal subset several land cover composition metrics were significantly correlated with fecal coliform. *Percent impervious surface* was significantly correlated with the geometric mean of combined wet and dry seasons fecal coliform measurements ( $R=0.62$ ,  $P < 0.05$ ). The geometric mean of fecal coliform measurements is also positively correlated with percent paved urban cover ( $R=0.68$ ,  $P < 0.01$ ), and mixed urban cover ( $R=0.70$ ,  $P < 0.01$ ), and negatively correlated with percent forest ( $R=-0.70$ ,  $P < 0.01$ ). While *percent forest* is also significantly negatively correlated with the geometric mean of the wet season fecal coliform measurements ( $R=-0.63$ ,  $P < 0.05$ ), percent urban and mixed urban cover are significantly correlated with the geometric mean of the dry season fecal coliform (respectively  $R=0.62$ ,  $P < 0.05$  and  $R=0.66$ ,  $P < 0.05$ ).

### 3.4 Landscape Configuration

*Cross-sectional sample:* Relationships between landscape configuration variables and fecal coliform were significant but not as strong a correlation across all 18 bays. Significant negative correlations were found between the *Aggregation Index of forest*, as measured by the Aggregation Index and Percent Like Adjacencies, and the combined measurements of fecal coliform for the combined wet and dry season ( $R=-0.52$  and  $R=-0.50$ ,  $P < 0.05$ ) and for the dry season alone ( $R=-0.65$  and  $R=-0.65$ ,  $P < 0.001$ ). This indicates that more fragmented forest is correlated with higher densities of fecal coliform. In addition the Aggregation Index and Percent

Like Adjacencies of Mixed urban land cover was highly correlated with density fecal coliform for the combined wet and dry season ( $R=-0.52$  and  $R=-0.50$ ,  $P < 0.05$ )

*Longitudinal land cover subset:* Stronger correlations were found between landscape configuration metrics and fecal coliform density for the longitudinal subset. In these sites, the landscape configuration metrics were significant for all land covers including forest, paved urban, and mixed urban. Fecal coliform measurements were negatively associated with aggregation of forest and positively associated with mixed urban cover as measured by the Aggregation Index (*AI forest*,  $R=-0.77$ ,  $P < 0.01$  and *AI mixed urban*  $R=0.77$ ,  $P < 0.01$ ) and Percent Like Adjacencies (*forest*,  $R=-0.75$ ,  $P < 0.01$  and *mixed urban*,  $R=0.77$ ,  $P < 0.01$ ). The fecal coliform measurements for the wet season were also positively correlated with the *Aggregation Index of paved urban* ( $R=0.65$ ,  $P < 0.01$ ) and *Percent Like Adjacencies urban* ( $R=0.66$ ,  $P < 0.01$ ).

### 3.5 Local Metrics

The landscape metrics measured in the local analysis (500 meter zone from the shoreline through the flow path or following the topography) showed significant correlations with fecal coliform density for *percent paved land* and *percent forest* for the wet season (respectively  $R=0.63$ ,  $P < 0.01$  and  $R=-0.67$ ,  $P < 0.01$ ). *Percent forest* was correlated with fecal coliform also for the combined seasons ( $R=0.49$   $P < 0.05$ ). Other landscape metrics such as local *road density* were not significantly correlated with fecal coliform in the 18 bays. The relationship between local variables and fecal coliform (for both land cover and road infrastructure) seem characterized by non-linear trends; but we could not confirm these results with the longitudinal basin land cover subset.

### 3.6 Regression Results

A set of apriori models are presented in Tables 20 and 21. We used intensity, composition, configurations, and two scales (basin and local) of metrics to explain the variance in the

geometric mean of fecal coliform for the three fecal coliform data sets: wet season, dry season, and the combined seasons. We compared them using adjusted  $R^2$ .

*Cross-sectional sample:* Percent forest explain 41 percent of the variance in the combined seasonal measures of fecal coliform and together with respectively road density and aggregation of forest cover explains almost half of the variance in measures of fecal coliform during the wet season. Percent paved also explain about 40 percent of the variance in fecal coliforms during the wet season. Population density, percent mixed urban cover, and aggregation of forest cover explain about 40 percent of the variance of fecal coliform in the dry season (Table 20).

*Longitudinal subset:* Land cover configuration is the best predictor of the variance in fecal coliform (combined seasons) in the longitudinal subset. The aggregation of mixed urban land cover and the aggregation of forest cover (respectively  $R^2 = .56$ ,  $p < 0.01$  and  $R^2 = .55$ ,  $p < 0.01$  Table 21). Population density, percent forest cover, and percent impervious surface are all significant in the combined seasons. During the wet season, the best predictor of the variance in fecal coliform is total road length ( $R^2 = .56$ ,  $p < 0.01$ ). During the dry season is the aggregation of forest cover ( $R^2 = .40$ ,  $p < 0.05$ ).

#### IV. DISCUSSION

The findings indicate that the land cover composition and configuration within the basins draining to the shellfish growing areas are good predictors of fecal coliform density. In particular, percent forest at the basin scale is strongly correlated with the geometric mean of fecal coliform measured across the bays both in the cross sectional and longitudinal subsets. The study shows also that a measurable difference in water quality can be detected across the Puget Sound in bays with different amounts of forest fragmentation and degree of aggregation of the urban cover at the basin scale. The AI of forest cover and the AI of Mixed Urban cover explained more than half of the variability in the geometric mean of fecal coliform in the longitudinal subset. Fecal coliform density is also significantly correlated with percent paved and total impervious area. Among the most urbanized basins the difference in water quality is also

associated with aggregation of impervious surface. This is particularly relevant since population growth is highly correlated with both decline in forest cover and increase in impervious surface in the central Puget Sound region.

Our results are consistent with previous findings from other studies where researchers have found a significant relationship between land cover and fecal coliforms (Weiskel et al. 1996; Mallin et al. 2001). While the amount of impervious cover in the basins provides a good measure of the human impact on the nearshore water quality, variables measuring its spatial configuration (i.e. aggregation of paved land) and connectivity (i.e. roads) show that the relationship between urbanization and water quality is not a linear one. Land use and wastewater infrastructure, among other factors, may also play an important role that influences the impact of increasing human population on coastal environments (Young and Thackston, 1999; Mallin et al. 2001). Other studies have shown that sites closer to areas with high densities of active septic tanks or more urbanized land uses tended to have higher fecal coliform densities (Lipp, 2001a; Lipp, 2002b; Kelsey et al. 2003). However, existing data to describe land use and infrastructure across the sampled sites need to be improved to test hypotheses on the role that these factors play in mediating the effects of urbanization on nearshore environments. The research could be further strengthened by the collection of water quality data tailored to the research objectives, such as consistent monitoring for historic records, rather than the requirements of the National Shellfish Sanitation Program.

The seasonal models (dry and wet) show that different variables, and therefore processes, may explain the release of fecal coliform pollution to the nearshore waters. While we did not include any meteorological variable (i.e. rainfall) in our models, different landscape metrics were significant for the combined, wet, and dry season measurements. In particular, while *percent forest*, *impervious area*, *road density*, and *local land cover areas* are important in explaining the wet season measurements, *population density* and *mixed urban cover* explain most of the variability across the sites for the dry season. The fact that land cover, specifically forest area and paved area, is a better predictor than population density for the wet season indicates that the effect of fecal input from surface runoff is suspected as perhaps one of the most important mechanism of fecal coliform pollution input to the estuary in urbanizing regions.

Together *amount* and *aggregation* of forest at the basin scale explain almost 50% of the variability in fecal coliforms in the wet season. Our analysis of the relationships between landscape metrics and fecal coliform within a 500-meter shoreline zone did show a significant correlation between the land cover composition at the local scale and fecal coliform density across the bays measurement. Our regression analysis indicated that together the *amount of forest* at the basin scale and *local road density* at the 500-meter local scale jointly explain fecal coliform density ( $R^2=0.45$ ,  $p<0.01$ ). However, since the basin and local variables were closely correlated, it is difficult to discriminate between these effects and assess their interactions through this study of the local interactions. However, the results do further reinforce the finding that forest cover and paved area are both strongly associated with fecal coliform densities. As we are unable to address the contribution of septic systems within the local zone, we suggest this as an area of further research.

This study has also pointed to substantive gaps in the information required to develop a robust assessment of the factors and mechanisms that link urbanization to fecal coliform pollution in Puget Sound. First, the depth of the fecal coliform data provided by DOH is not consistent across the bays. Only 18 out of 32 sites selected for the study were retained after standardizing the procedure for producing a statistically valid data set. In addition, important environmental and meteorological data were not available for all of the sampled sites, which limited the interpretation and analysis of the variability across the selected basins. The data sources for tidal mixing, tidal stage, temperature and salinity were not accessible for the analysis of 32 bays within the limited resources and scope of this project. We also identified an important gap in the land use data across the eleven Puget Sound counties where the 32 sites are located. Although important progress has been made in compiling these data by the assessor offices of counties and cities, these data are still too incomplete, inconsistent and inaccurate to be used in landscape analyses. However, the greatest gap is data on the wastewater infrastructure. Lack of data on the density and age of septic systems, wastewater systems, drainage networks and curb-gutter-pipe systems is the greatest limitation since it hinders our ability to assess the role that wastewater infrastructure plays in mediating the effect of urbanization.

## V. CONCLUSIONS

The findings of this study indicate significant statistical relationships between landscape patterns and fecal coliform density in shellfish growing areas. Percent forest cover and its fragmentation are the best predictors of fecal coliform across the selected bays studied. The amount of impervious surface is also a good predictor of water quality conditions in the eighteen bay areas. The multi-regression analysis also indicates that possible interactions exist between the local (amount of impervious surface) and basin-scale (amount of forest) landscape composition in the dynamics of fecal coliform pollution. These findings suggest that stormwater runoff may be the leading mechanism of fecal coliform pollution and contamination of shellfish in coastal areas. Data limitations have constrained the possibility to assess the role that wastewater infrastructure plays in influencing the impact of landscape change in this study. Many counties do not have digital files or historic records of septic systems, drainage networks or outfalls. However, the findings show that land cover composition and configuration are reliable indicators of the aggregated impacts of urbanization in coastal areas.

Increasing development of coastal areas in Puget Sound is likely to continue in the coming decades. However the pattern of development can be guided in ways that minimize its impact. Efforts to minimize the adverse effects of urbanization on shellfish growing areas should occur at multiple scales from the basin to the local scales and simultaneously aim at both minimizing the development of impervious surface and the clearing of forest cover. Furthermore in this study we have shown that the configuration of the land cover, not only its composition, may play an important role in the dynamic of fecal coliform pollution. Forest conservation and smart growth strategies should help limit the degree of alteration of both basin and local scale hydrological processes and consequent adverse effects on nearshore environmental conditions that sustain safe shellfish harvesting.

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## **DEFINITIONS OF TERMS**

### **ArcView 3.2, ARC/INFO & Arc Map 8**

ArcView 3.2, ARC/INFO and ArcMap 8 are geographical information system (GIS) software packages that were developed by Environmental Systems Research Institute (ESRI). A variety of applications and tools from these packages were used to process data for this analysis.

### **Basin**

Commonly, a basin refers to an area of land that drains surface runoff to a common collection point or body of water. In this study, we used the basin contributing surface runoff to a bay as the associated landscape for our analysis.

### **Buffer**

A buffer is a zone of specified distance around a selected landscape feature based upon a chosen attribute of a layer of data. Buffers are used in this study to create zones of analysis within a certain distance of the shoreline (for example 500 meters).

### **Composition Metrics**

Composition metrics measure the content of spatial features of a unit of the landscape. Examples include proportions, evenness and dominance of a particular landscape type.

### **Configuration Metrics**

Configuration metrics measure the spatially-explicit characteristics, organization or arrangement of landcover types within a defined unit of the landscape. Examples of configuration include size, shape, and ratio of landcover patches.

### **Connectivity**

Connectivity refers to linkages or systems that connect one landscape unit to another. Networks of roads, surface water flows and drainage systems are examples of landscape connectors.

### **Cost Distance**

As a program function in GIS software, a cost distance is a measure of distance between a source cell and a selected target cell. Instead of calculating distance as a straight linear distance, the cost distance is calculated by moving through cells provided as a source grid, in this case water pixels. The cost distance was calculated by moving through the water pixels to all edge pixels within a selected distance.

### **Digital Elevation Model (DEM)**

A digital elevation model is a grid file where each cell contains an attribute relating to its elevation. This project used a 30 meter DEM supplied by the United States Geological Survey.

### **FLOWLENGTH command**

The FLOWLENGTH command calculates the stream distance to the stream mouth by calculating the in-channel distance (rather than a straight linear distance).

**Intensity Metrics**

Intensity metrics measure the degree to which the land is used for a certain socioeconomic purpose, such as the total percent of the landscape devoted to single-family residential housing or total number of roads in a given area.

**Landscape Metrics**

Landscape metrics are methods of measuring or quantifying the patterns or characteristics of the landscape at a set point in time.

**Patch**

A patch is an identifiable landscape element that differs from its surrounding areas. The patch is considered to be internally similar, such as a forest area is internally similar and distinguishable from a neighboring grassland patch.

**Pixel**

Pixel is short for picture element. It is the smallest dissolvable unit in an image or grid data set. Pixels may have a spatial coordinates (x,y), values or assigned attributes.

**Pour Point**

A pour point is an outlet at which water flows out of an area, such as a stream outlet into a bay. In order to capture all surface flow, all shoreline pixels were considered pour points for small surface drainages that do not contribute to streams before entering a bay.

**Sub-basin or Sub-watershed**

A sub-basin or sub-watershed refers to a portion of a watershed that drains to a particular point within a larger drainage or basin. The uplands that collect to create a stream form a sub-basin or watershed for a larger watershed.

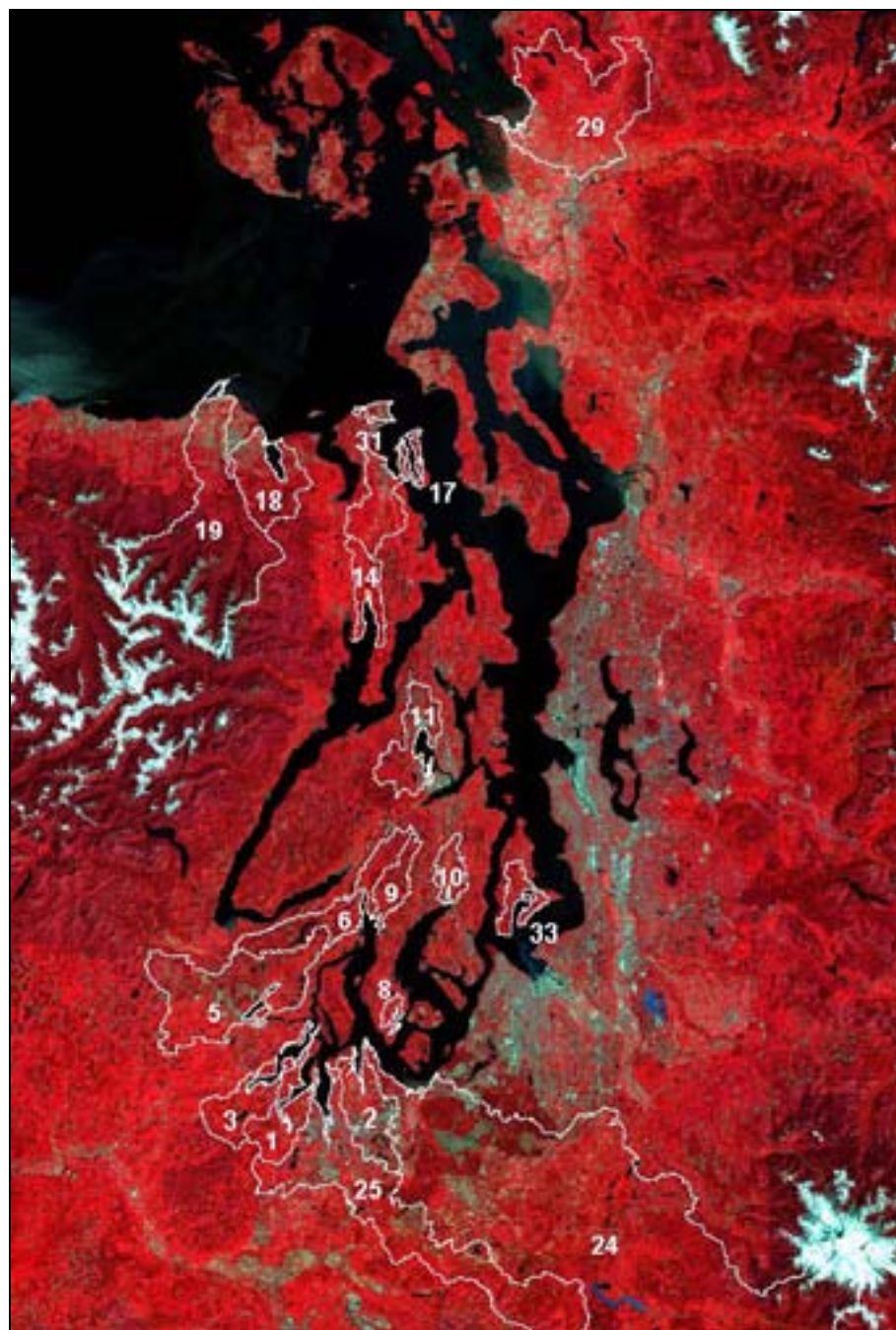
**Watershed**

A watershed is an area that drains water and other substances to a common outlet through overland surface flow, and in certain locations such as cities, drainage infrastructure. Watersheds are bounded by a drainage divide or ridge separating watershed units.

**WATERSHED command**

The WATERSHED command is a program function of ARC/INFO geographic information system software. It delineates, or defines, the extent of a watershed using an digital elevation grid to find the highest point or ridge. It then returns a file that has only the points associated with a common drainage point.

**Figure 1. Study of Urbanization Impacts on Shellfish Growing Areas within Puget Sound**



Selected Study Sites (18)

Burley Lagoon—10  
 Dabob Bay—14  
 Dyes Inlet—11  
 Eld Inlet—1  
 Filucy Bay—8  
 Henderson Inlet—2  
 Kilisut Harbor—17  
 North Bay—6  
 Oakland Bay—5  
 Rocky Bay—9  
 Quartermaster Harbor—33  
 Totten Inlet—3  
 Budd Inlet—25  
 Dungeness Bay—19  
 Nisqually Reach—24  
 Port Townsend—31  
 Samish Bay—29  
 Sequim Bay—18

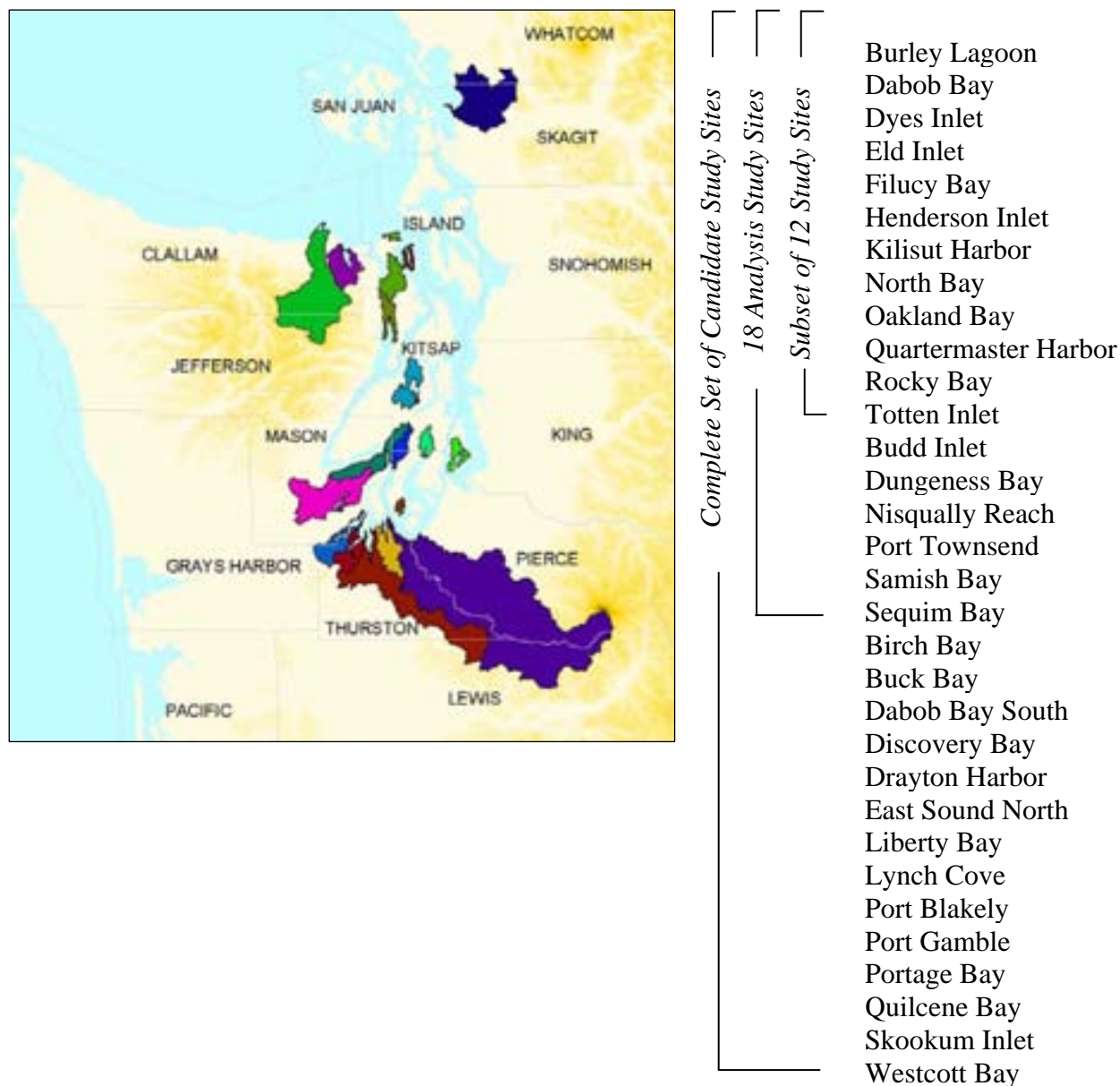
Candidate Sites- not shown

Buck Bay  
 Dabob Bay South  
 Quilcene Bay  
 Westcott Bay  
 Discovery Bay  
 Skookum Inlet  
 East Sound North  
 Port Gamble  
 Lynch Cove  
 Drayton Harbor  
 Port Blakely  
 Birch Bay  
 Liberty Bay  
 Portage Bay

Note: We make an important distinction that the boundaries of the study areas were determined to coincide with the DOH water quality stations (1500 meters from any of the bay's stations). Therefore due to the limits of the water quality monitoring locations, the study area may not include the entire bay or waterbody such as in the case of Port Townsend. Due to the location of the stations, Port Townsend is split into two sub-basins for this analysis.

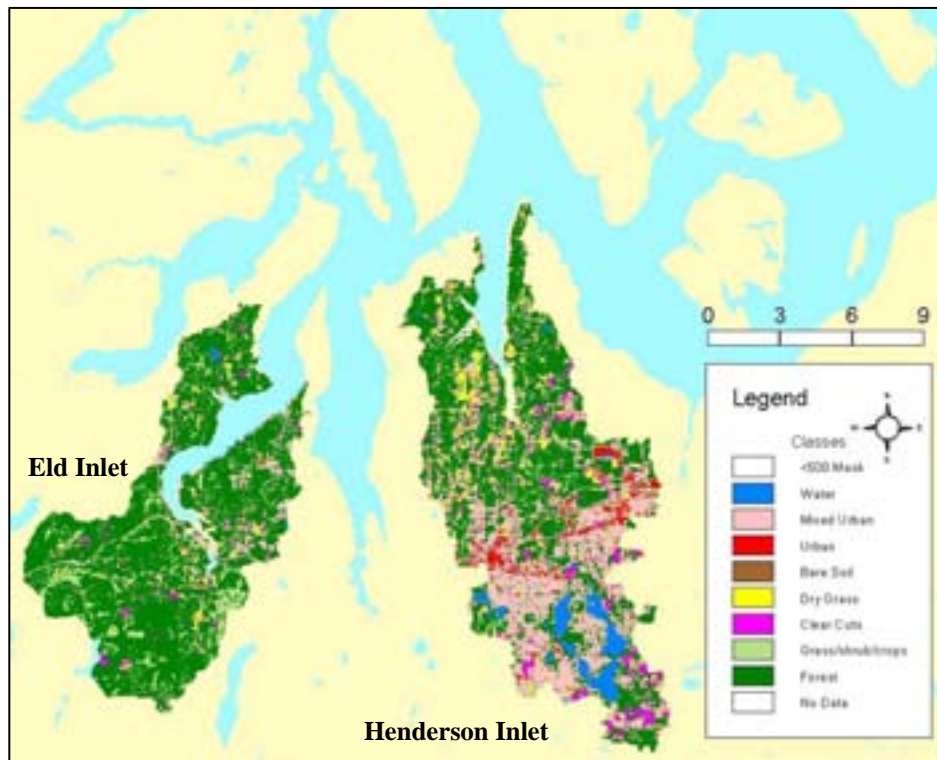
## Figure 2. Distribution of 18 Study Sites within Puget Sound

The watersheds cross boundaries of 11 counties, including public, private, tribal and military lands. They represent both geographical distribution and a gradient of development from urban to rural.



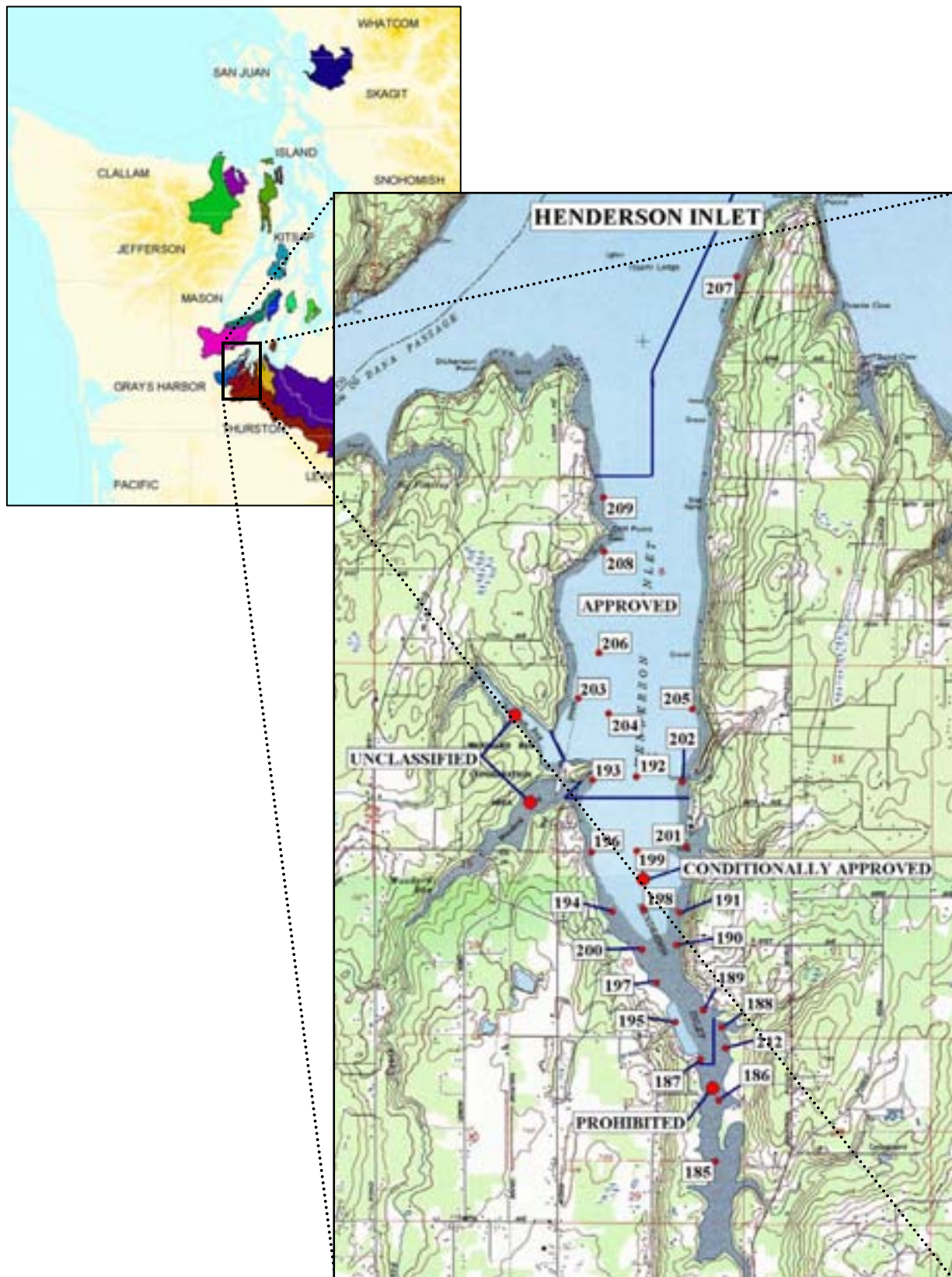
### Figure 3: Comparison of Landscape Patterns for Two Puget Sound Basins

The two basins featured in the box below illustrate the differences in land cover and water quality.



Characterization	Eld Inlet	Henderson Inlet
Population Density	low density	mod / high density
Total Area	89.1 total sq.km	120.4 total sq.km
Urban Area	2.37 urban sq.km	35.4 urban sq.km
Growing Area Classification	Approved	Approved, Conditional and Closed

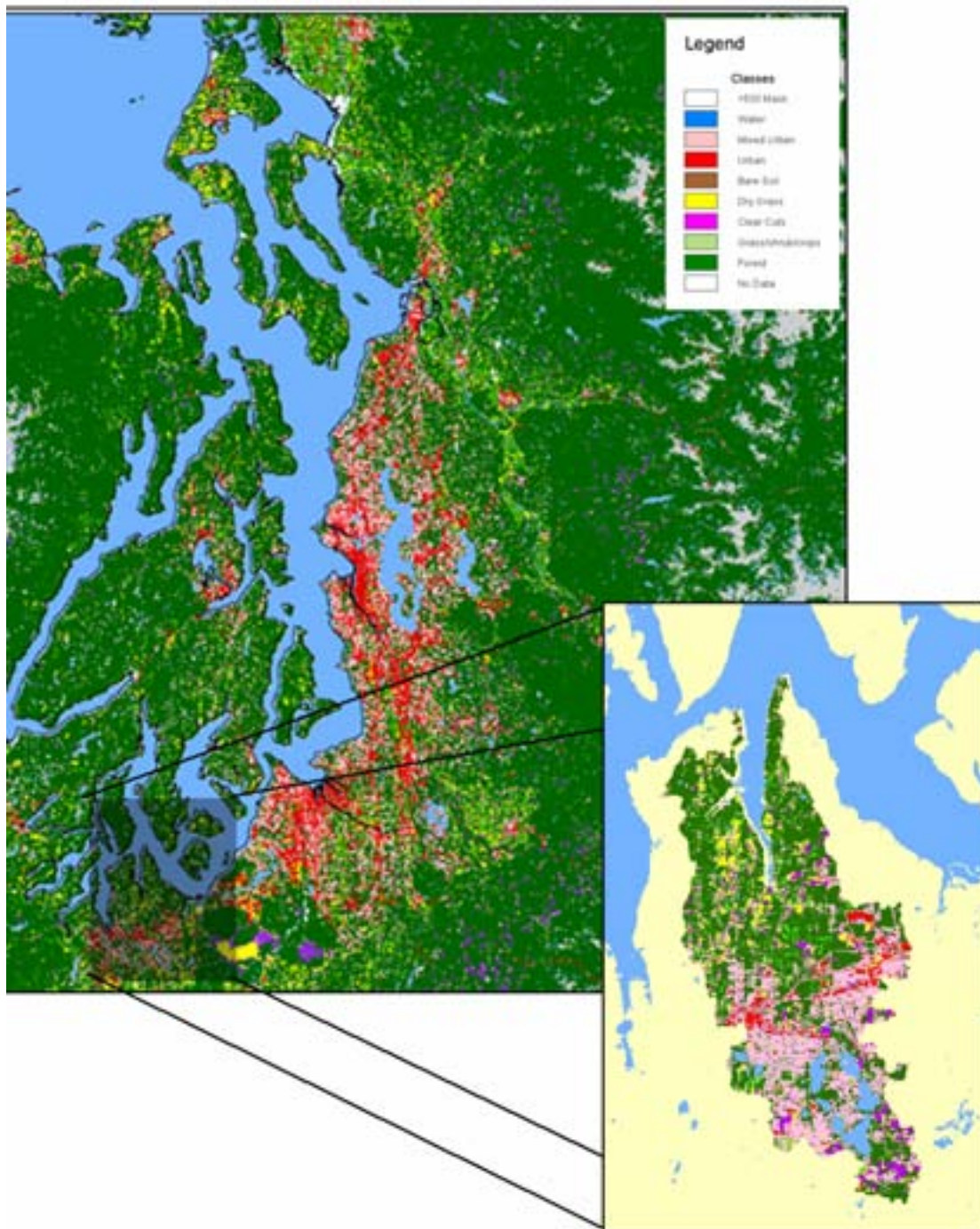
Figure 4. Examples of DOH Water Quality Monitoring Stations



Source: DOH, 2004.

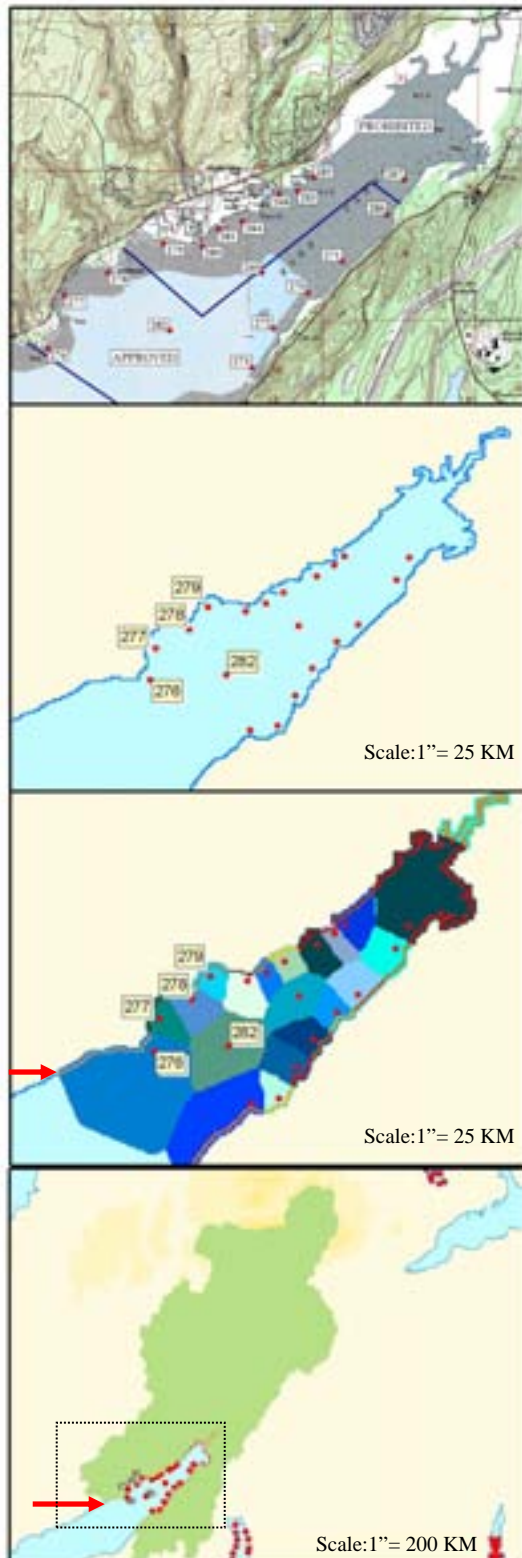
**Figure 5. Watershed Delineation and Characterization**

We defined the boundaries and assessed the characteristics of each watershed using a series of landscape metrics. The inset shows the 2002 Land Cover Classification for Henderson Inlet.



### Figure 6. Example of Cost Distance Grid Calculation Process

We calculated a cost distance grid of 1500 meters from each DOH water quality station to the coastline to produce pour points. Watersheds were delineated for each basin combining the results of each pour point to represent the total fresh water inputs into each bay.



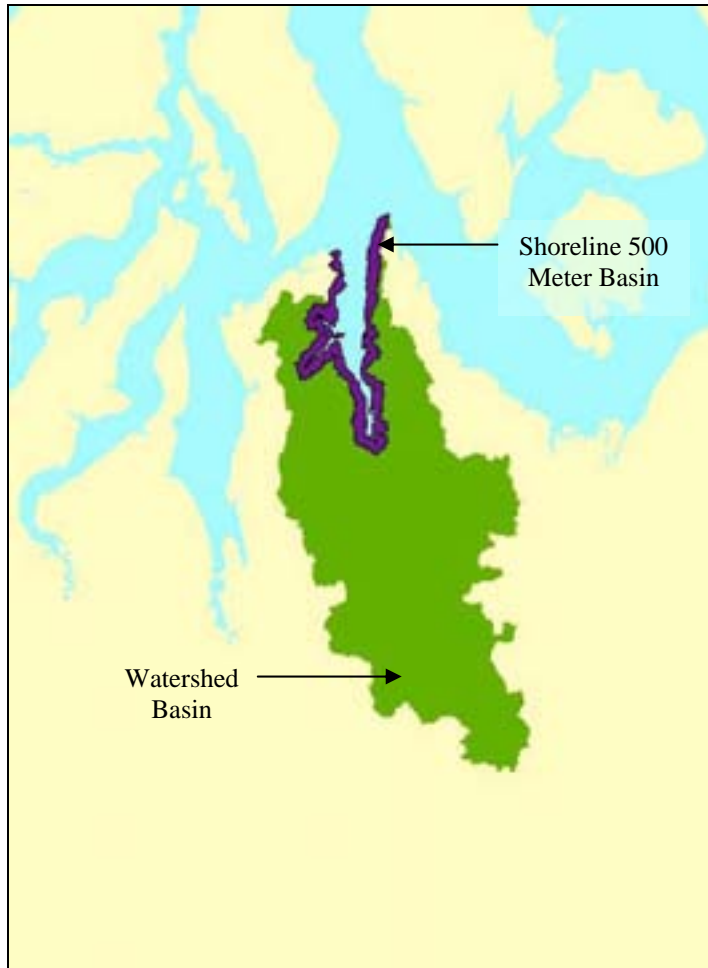
The basic unit of landscape analysis is the watershed basin that contributes to a water body. The purpose of the Cost Distance Process was to determine what landscape areas influence the water quality stations for our analysis. The first step was to isolate the shoreline pixels that could be used as pour points for the watershed delineation process. The question answered by this process was “what shoreline pixels are 1500 meters from the water quality monitoring stations in each bay.” Water quality monitoring stations from Lynch Cove will be used for this example.

1. Data Preprocessing: Digital elevation models and water quality station locations are pre-processed for the cost distance process. The red dots are the water quality monitoring stations (276, 277, 278, etc). The bright blue cells are the individual shoreline pixels of the DEM; the light blue cells are open water cells of Lynch Cove.
2. Cost Distance Grid Calculation: A distance of 1500 meters was calculated for each cell across the water surface. The cost distance function calculates the distance of each cell to the monitoring station. The cells are assigned to the monitoring station that the closest to the cell. In the example, the shoreline cells associated with station 276 end at the red arrow in the diagram. This is the furthest extent of the shoreline pixels associated with Lynch Cove for this study.
3. Watershed Delineation: The shoreline pixels from each water quality monitoring station are aggregated and used to delineate the watershed for each basin. The process results in a continuous section of shoreline to be used as pour points for each basin to capture both stream contributions and surface flow into the study bays. The final box shows the extent of Lynch Cove watershed after the delineation process is completed.

Source: Urban Ecology Research Laboratory

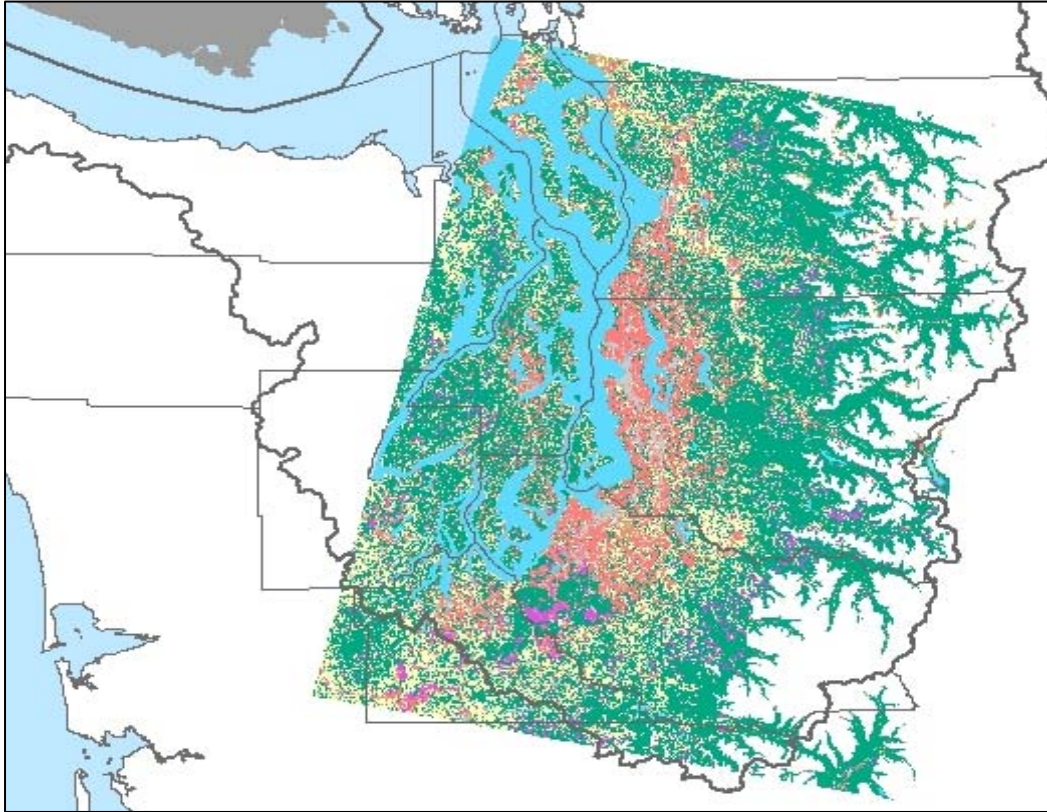
**Figure 7. Scales of Analysis: Basin and Local 500 Meter Shoreline Zone**

Two scales of analysis were utilized: the basin scale and 500 meter distance from the shoreline upland through the flow path. We measured landscape patterns at both scales.



Source: Urban Ecology Research Laboratory

**Figure 8. UERL 1991 & 1999 Land Cover Change Classification:** Land cover classification data from 1991 and 1999 were used to conduct a landscape change analysis for the Central Puget Sound area. As a landscape analysis tool, comparisons of two land cover classifications eight years apart enable changes in the landscape to be measured and contrasted for different development scenarios.



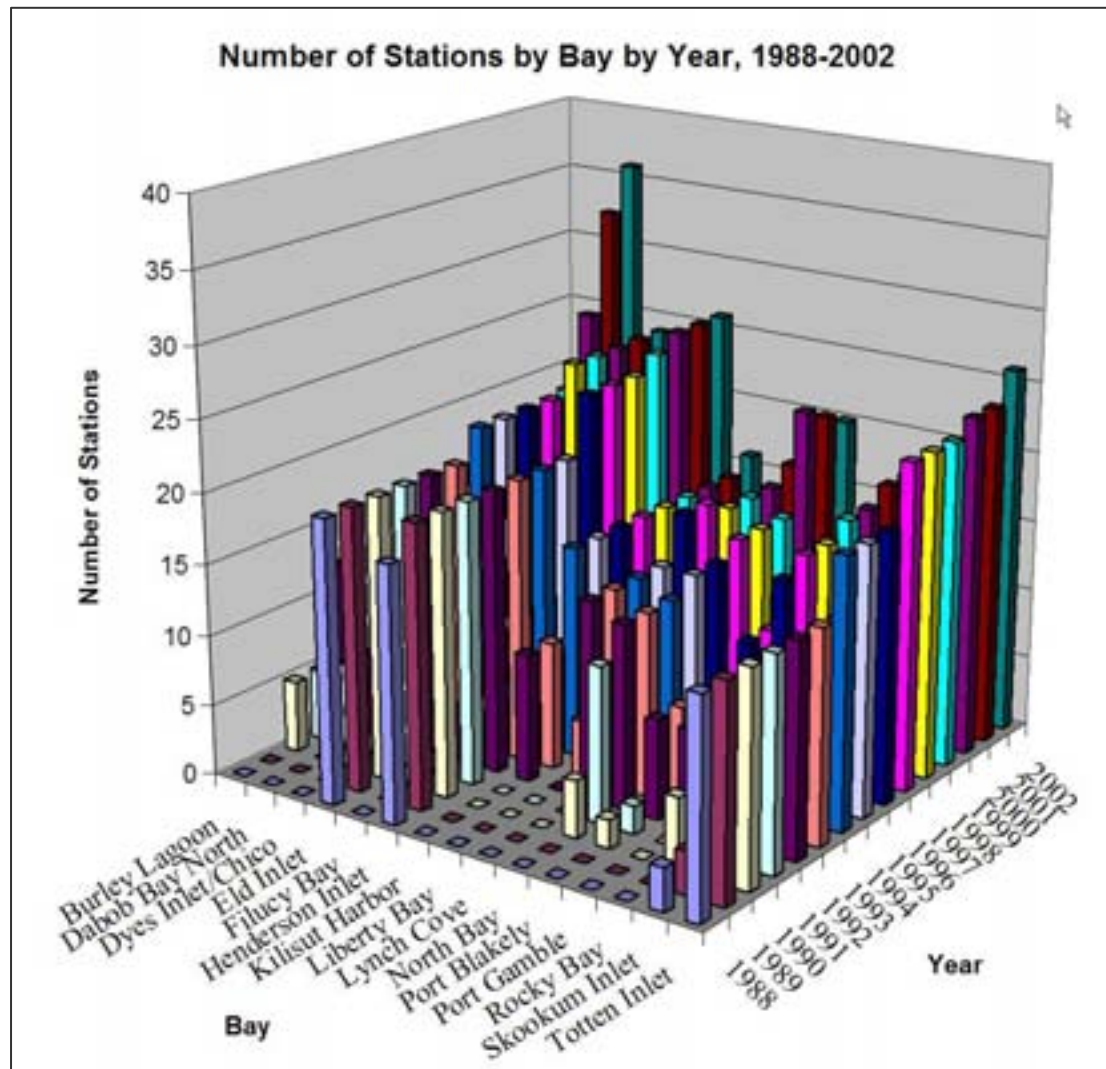
Source: Urban Ecology Research Laboratory

**Figure 9. UERL 2002 Land Cover Classification:** This classification incorporated both supervised and spectral unmixing classification techniques for the entire Puget Sound area.

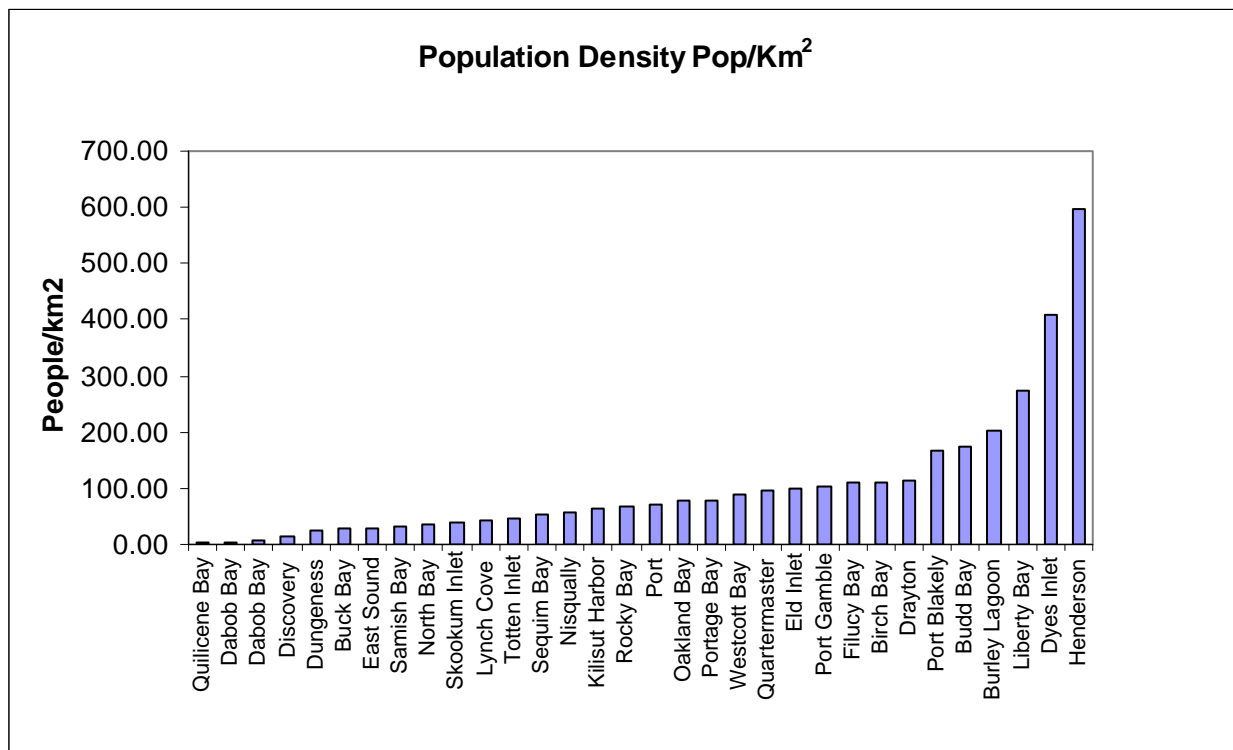


**Figure 10: Example of Water Quality Stations per Basin per Year for 15 Selected Basins:**

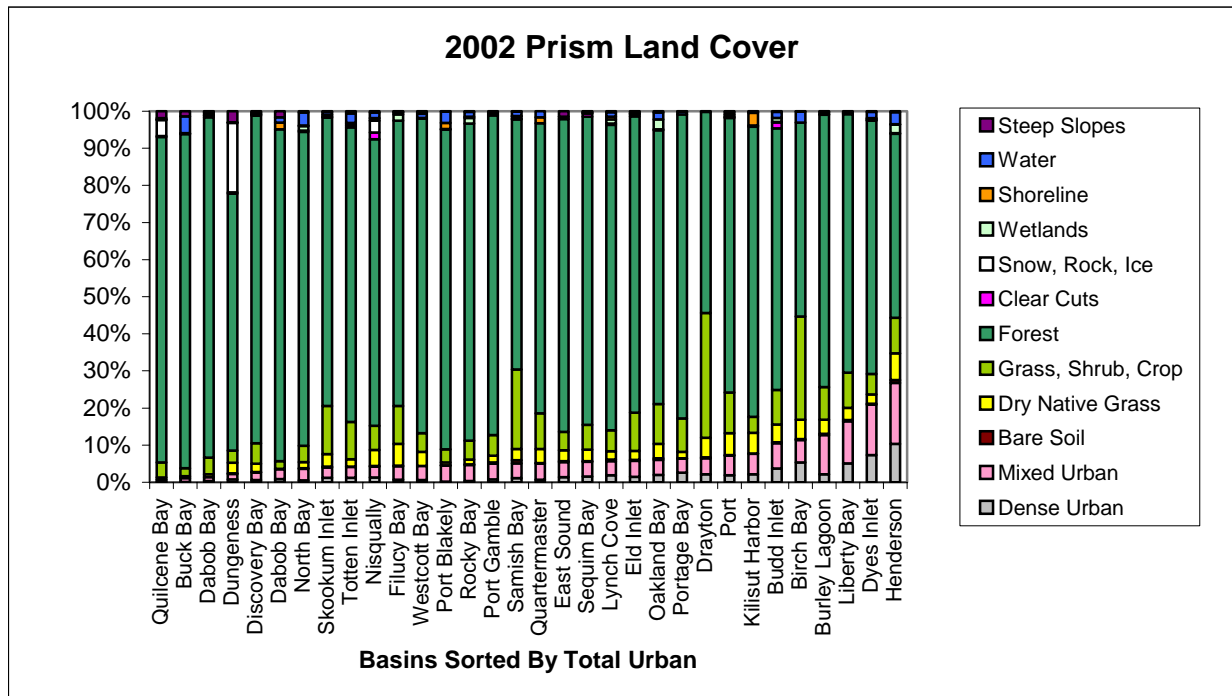
This figure shows the distribution of the number of water quality stations for 15 Puget Sound stations within each bay from 1988-2002. The graph represents the range of measurement across the bays included within this study.



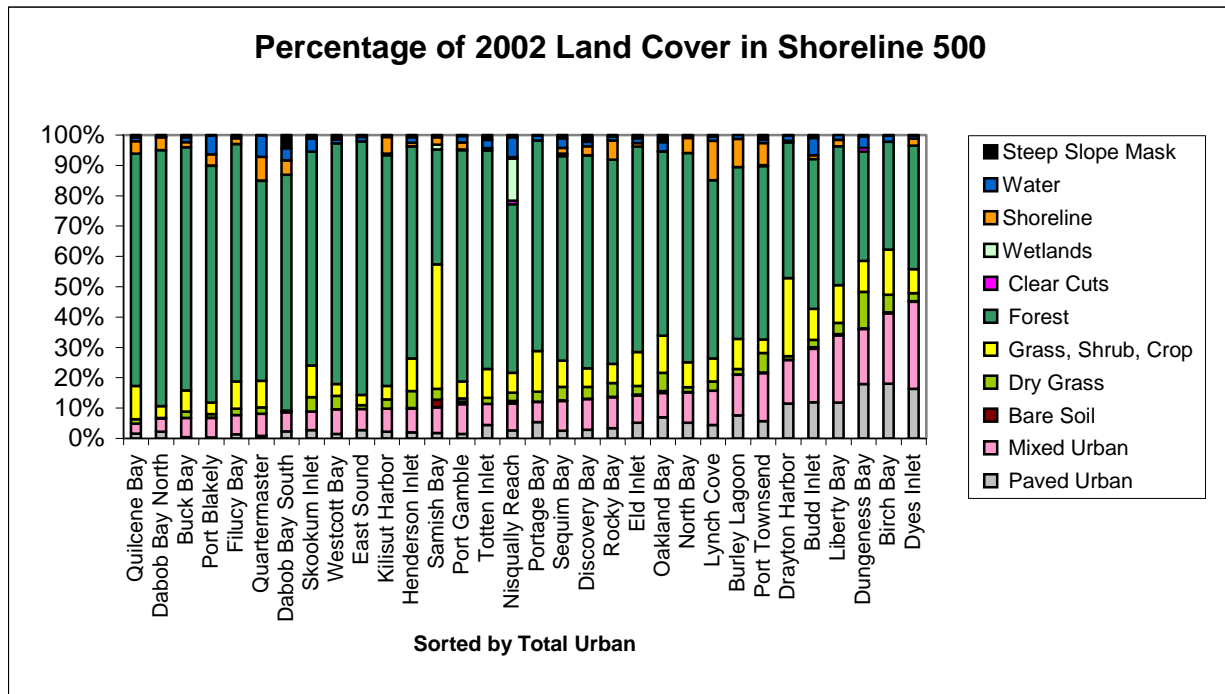
**Figure 11. Population Density for 32 Candidate Watershed Basins**



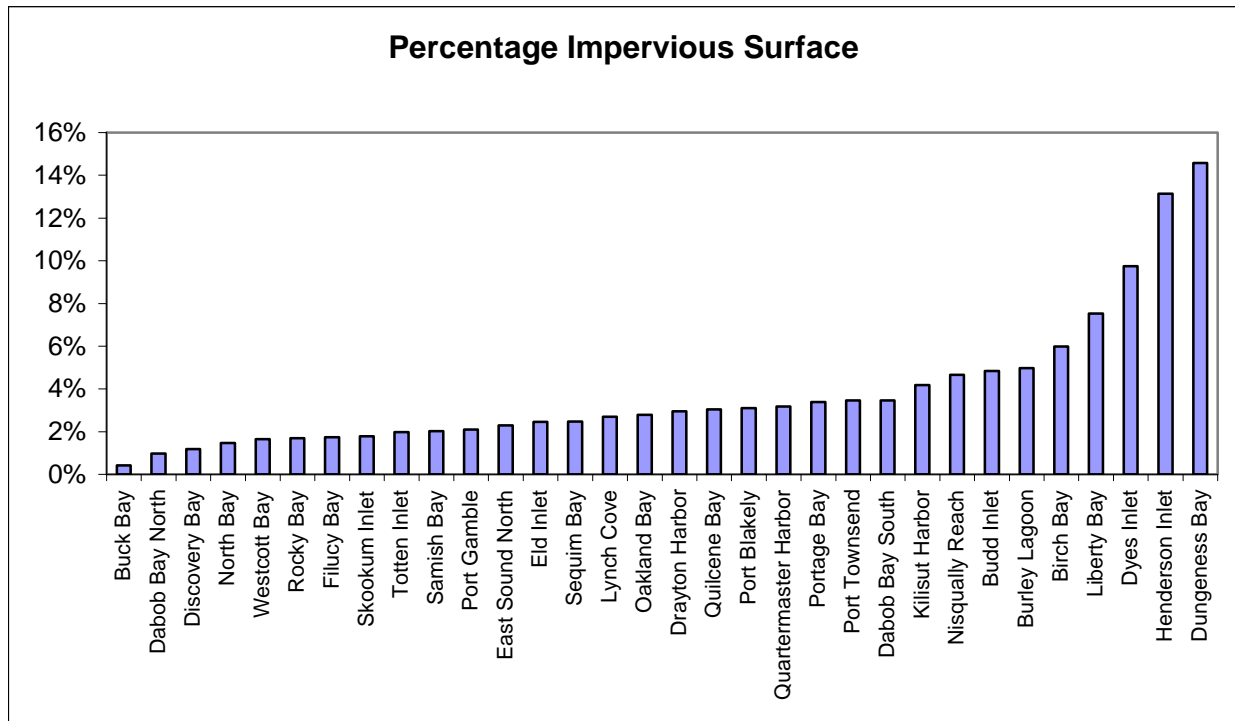
**Figure 12. 2002 Land Cover Distribution for 32 Candidate Watershed Basins**



**Figure 13. 2002 Land Cover Distribution for 500 Meter Shoreline Zone**

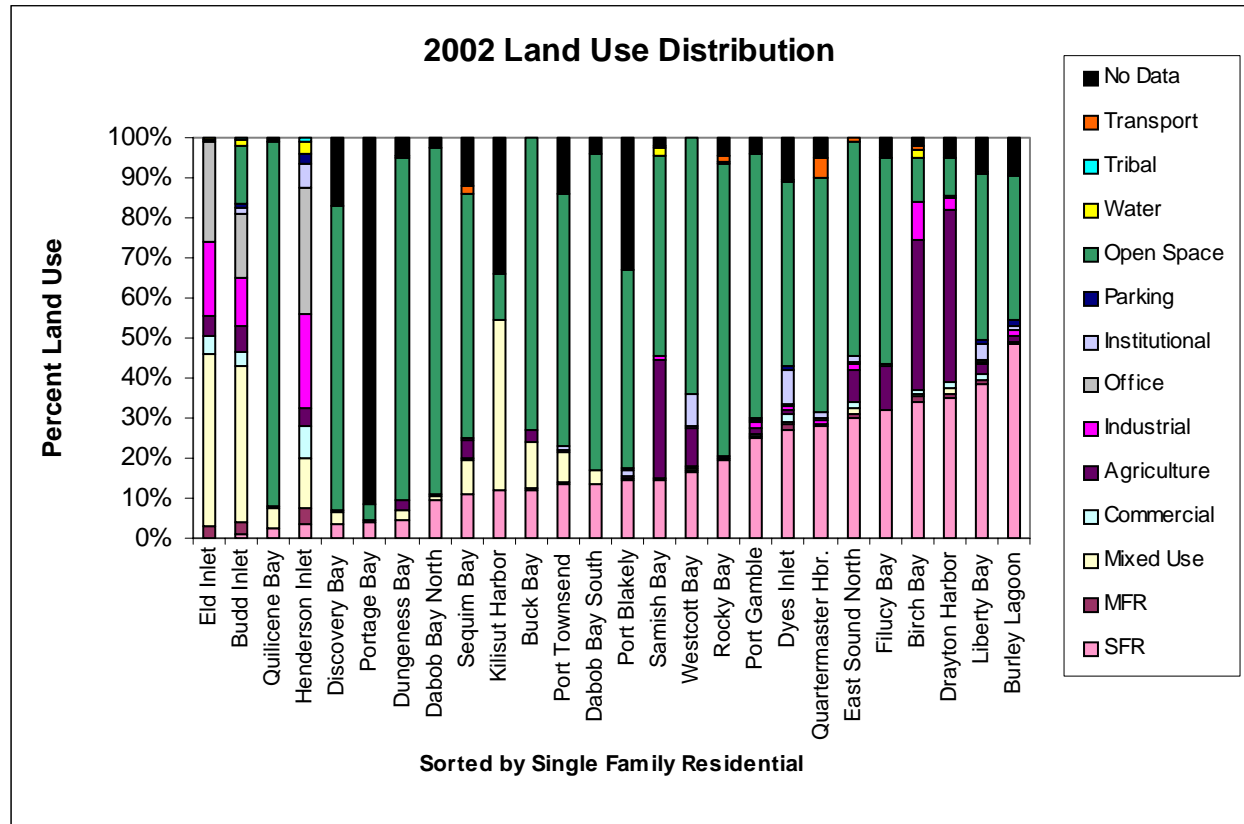


**Figure 14. Percentage Impervious Surface for 2002 Land Cover for 32 Candidate Basins**



**Figure 15. 2002 Land Use Distribution for 26 Basins**

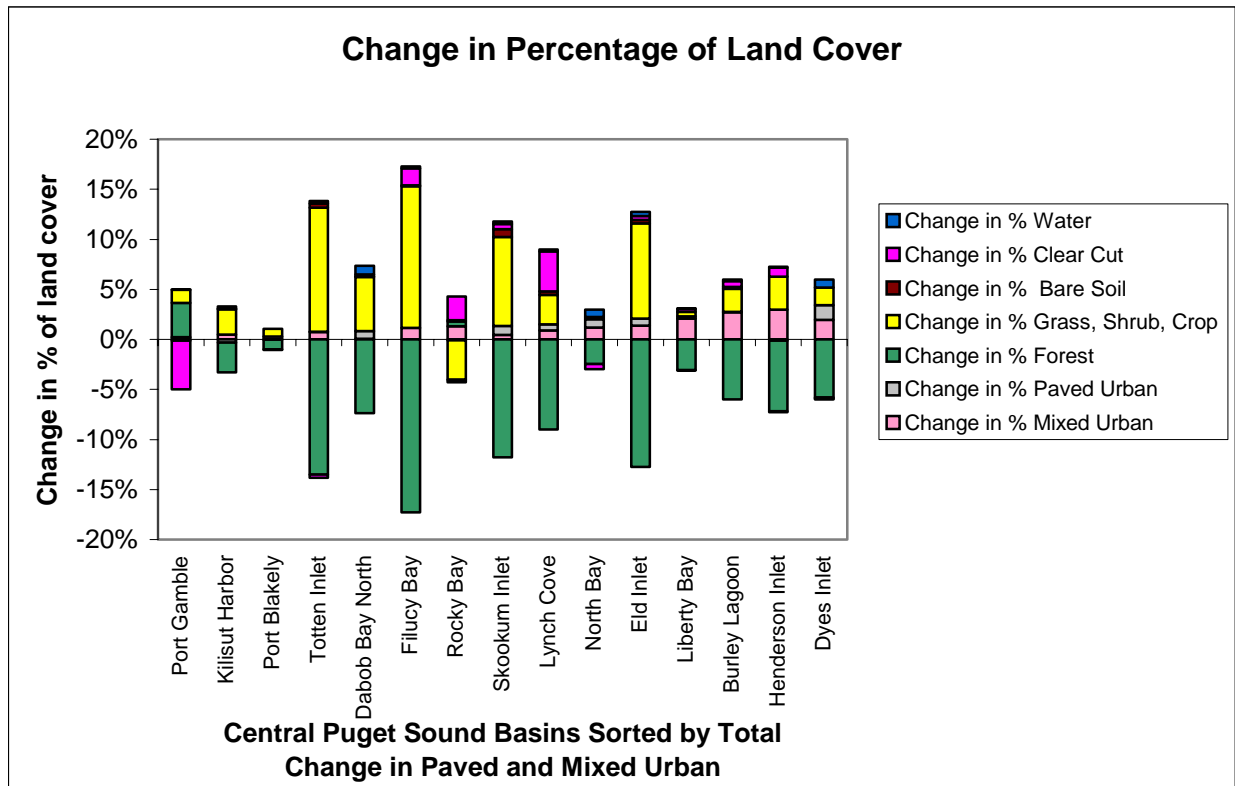
Land use data was not available for all basins and several basins have large portions of unknown land use parcels. The 26 basins presented here show the extent of information available for land use at the time of this project.



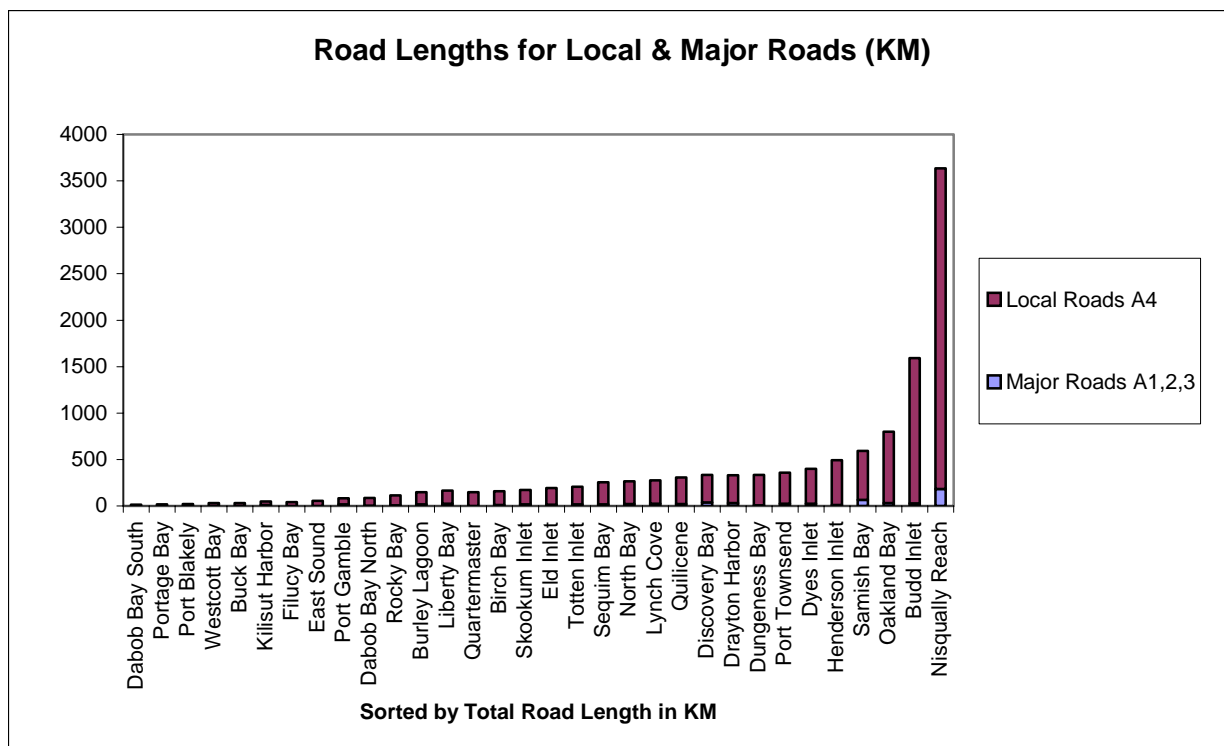
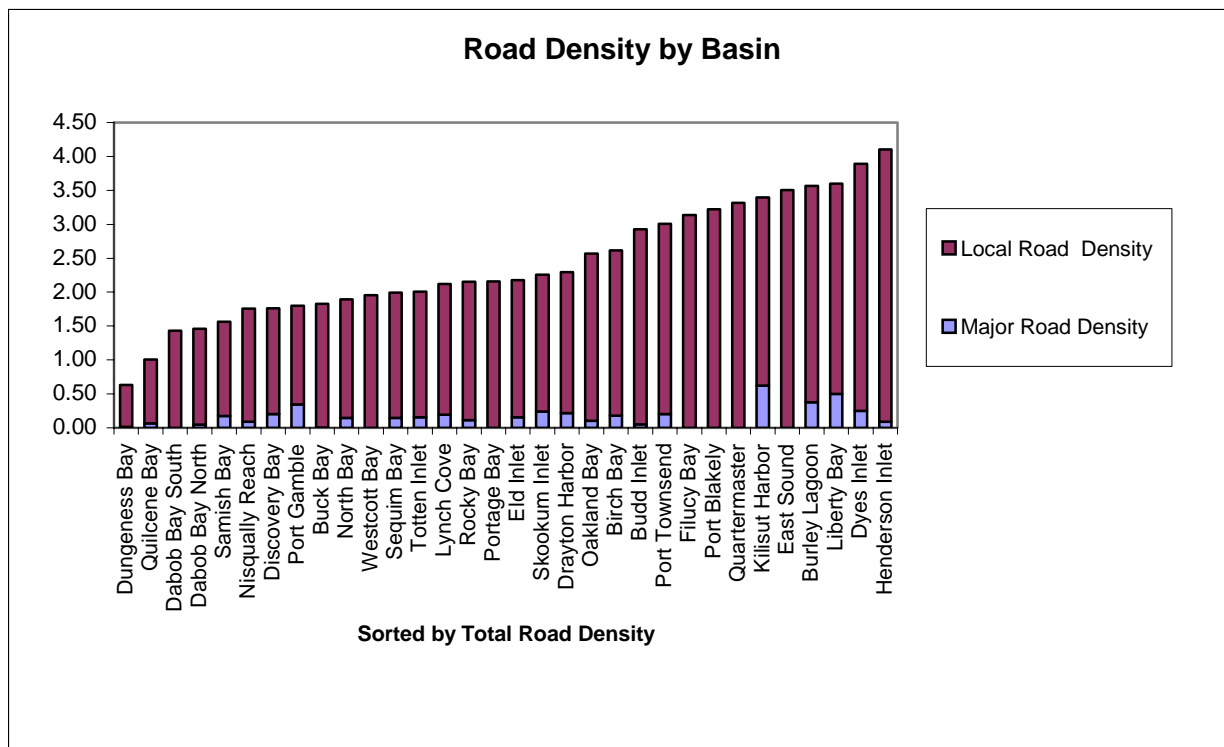
### Land Use Category Descriptions

Abbreviation	Category	Description
No Data	No Land Use Data	Parcels of land with no land use data available
Transport	Transportation Infrastructure	Linear roads, arterials, streets, alleys, utilities
Tribal	Tribal	All Indian reservation land includes all activities
Water	Water	Open water areas,
Open Space	Open Space	Protected or undevelopable land, open space,
Parking	Parking	Parking lots and facilities
Institutional	Institutional	Schools, churches, government, hospitals, etc.
Office	Office	Service/office without retail: doctor, real-estate, etc.
Industrial	Industrial	Light manufacturing
Agriculture	Agriculture	Farms - poultry, dairy, crops, and livestock
Commercial	Commercial	Businesses: hotels, sales, retail, trade, hatcheries,
Mixed Use	Mixed Use	Combined residential and commercial uses mixed
MFR	Multi-Family Residential	Duplex, triplex, apartment building
SFR	Single Family Residential	Single family residential, bed & breakfasts, etc.

**Figure 16. Land Cover Change 1991-1999 for 15 Selected Basins**

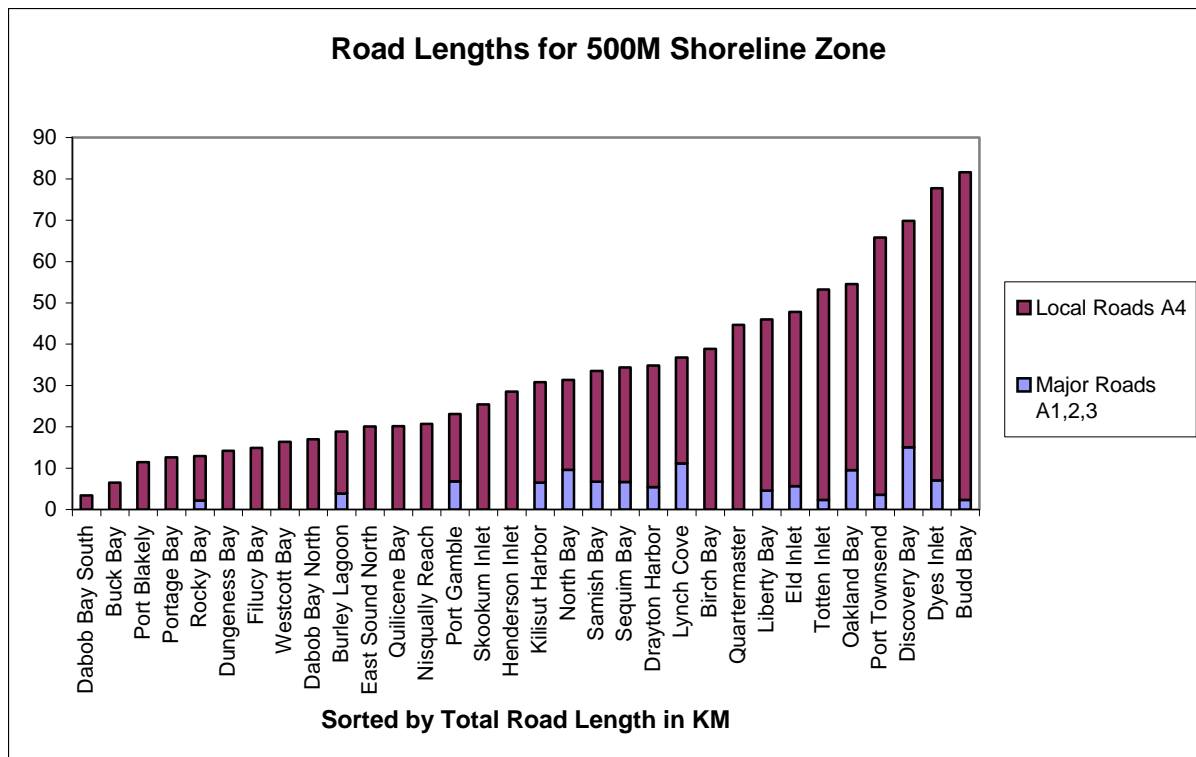
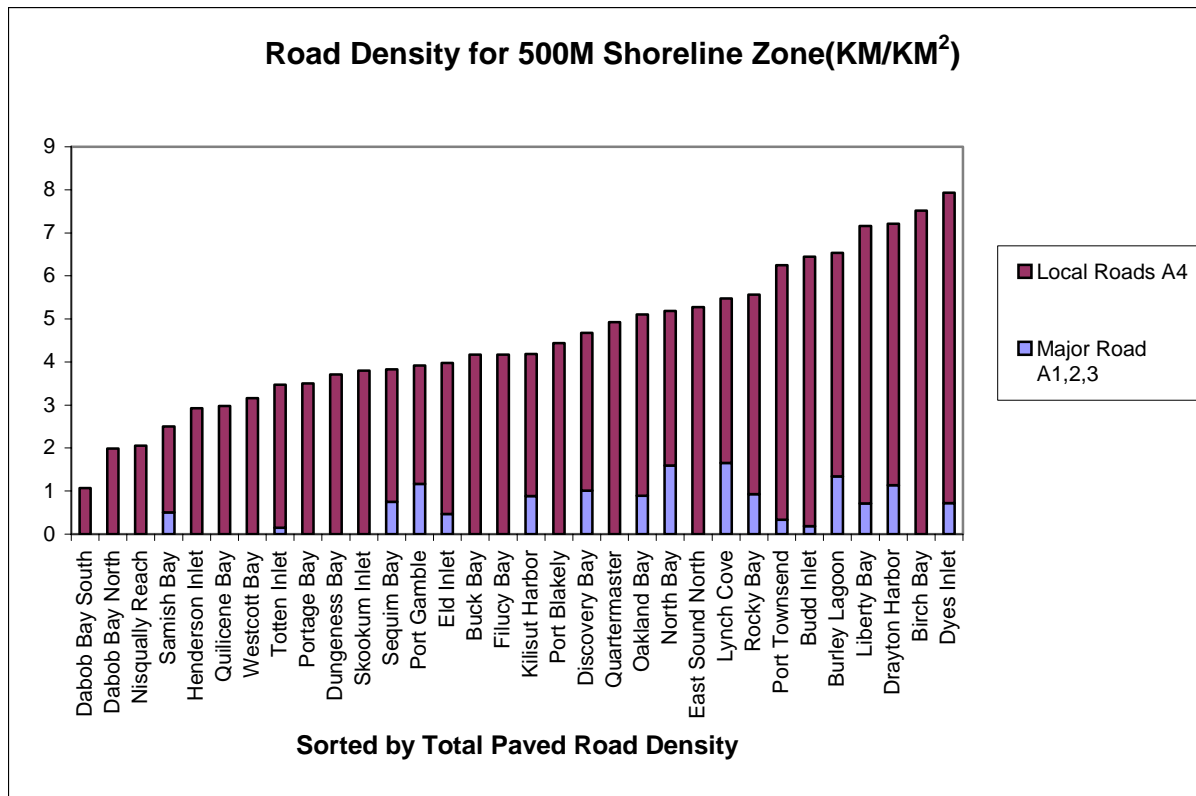


**Figure 17. 2000 Road Density and Lengths by Basin** The data for this analysis utilized Washington State TIGER road data. Major roads are classified as TIGER category A4 and local roads are classified as TIGER categories A1-3.

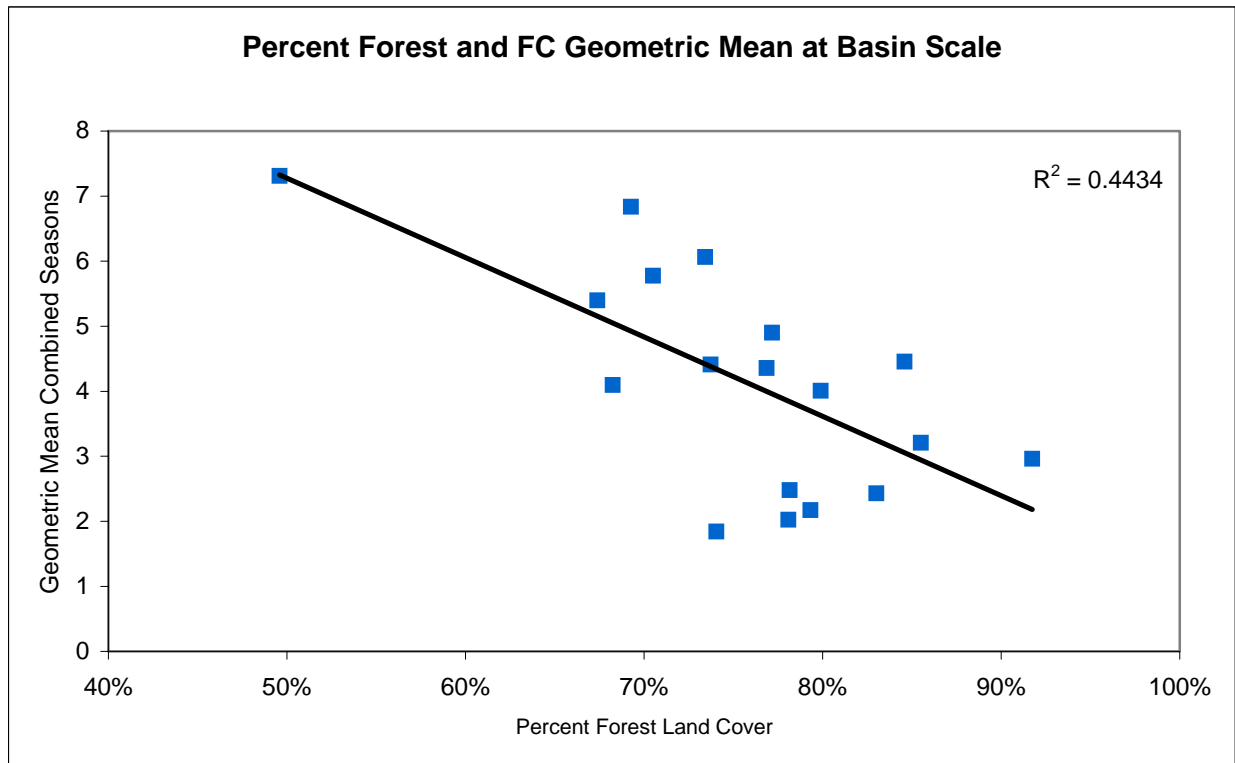


**Figure 18. 2000 Road Density and Lengths for 500 Meter Shoreline Zone**

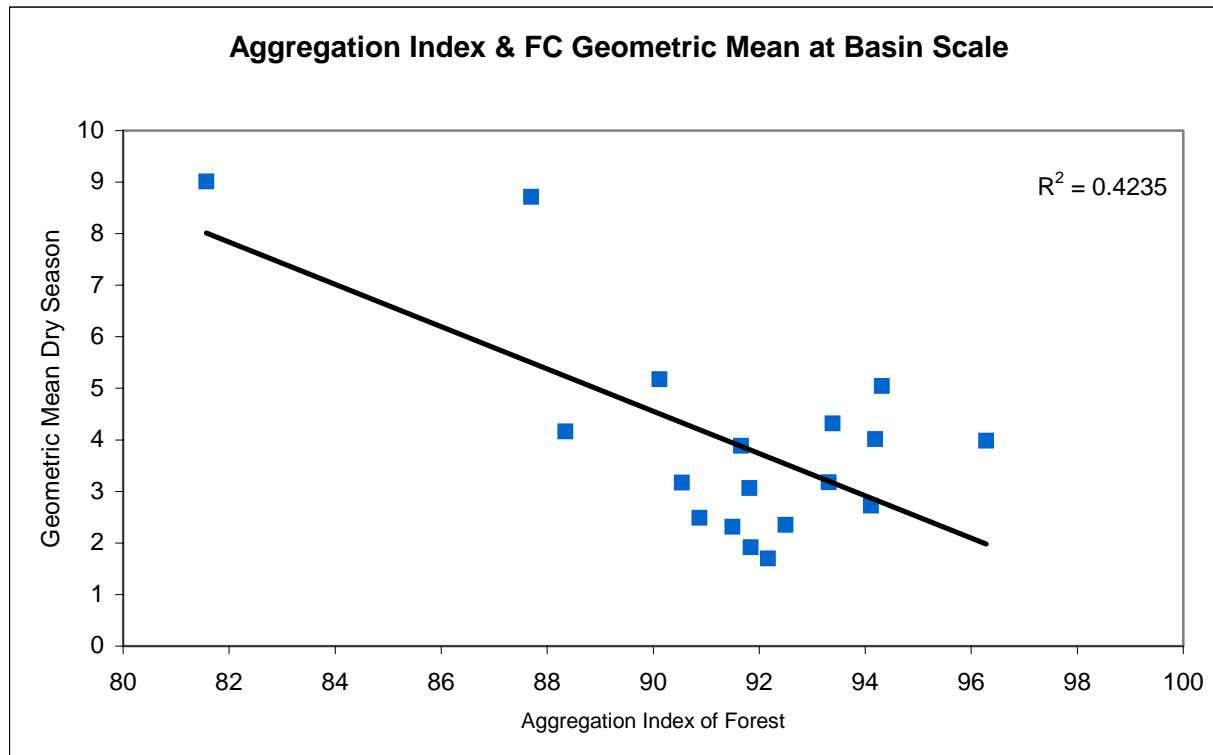
The data for this analysis utilized Washington State TIGER road data. Major roads are classified as TIGER category A4 and local roads are classified as TIGER categories A1, A2 and A3.



**Figure 19. Percent Forest Cover and Fecal Coliform Geometric Mean for 2022 Land Cover**



**Figure 20. Aggregation Index of Forest and Fecal Coliform Geometric Mean**



**Table 1. Size and Percent Impervious Area for 18 Study Sites\***

Basin	Area (km <sup>2</sup> )	Area (km <sup>2</sup> ) Below 500M Elevation*	Percent Basin Below 500M Elevation	Percent Impervious Area	Impervious Area (km <sup>2</sup> )	Cross-sectional Sample	Longitudinal Land cover subset
Burley Lagoon	41.72	41.74	100%	5.0%	2.08	*	*
Dabob Bay	59.21	59.25	100%	1.0%	0.57	*	*
Dyes Inlet	102.59	102.61	100%	9.7%	9.99	*	*
Eld Inlet	89.10	88.88	100%	2.5%	2.19	*	*
Filucy Bay	13.44	13.44	100%	1.7%	0.23	*	*
Henderson Inlet	120.36	120.37	100%	13.1%	15.80	*	*
Kilisut Harbor	14.28	14.29	100%	4.2%	0.60	*	*
North Bay	140.69	140.71	100%	1.5%	2.07	*	*
Oakland Bay	310.98	311.04	100%	2.8%	8.68	*	*
Quartermaster Harbor	44.20	44.23	100%	3.2%	1.41	*	*
Rocky Bay	52.36	52.36	100%	1.7%	0.89	*	*
Totten Inlet	102.58	101.59	99%	2.0%	2.03	*	*
Budd Inlet	544.43	458.90	84%	4.9%	26.40	*	
Dungeness Bay	527.62	122.90	23%	14.6%	76.88	*	
Nisqually Reach	2069.17	1189.57	57%	4.7%	96.63	*	
Port Townsend	119.20	119.21	100%	3.5%	4.12	*	
Samish Bay	378.85	336.75	89%	2.0%	7.69	*	
Sequim Bay	127.25	100.56	79%	2.5%	3.16	*	

\* Area (km<sup>2</sup>) below 500M Elevation: This measure of land area calculates the amount of each basin that is within the land cover classifications used for this study. Land area above 500 meters was not classified in the 1991 and 1999 UERL land cover process. For 2002, landscape metrics were calculated using total basin area. For landscape metrics calculated from 1991 and 1999 land cover data (e.g. percent forest, percent impervious surface, etc.) the area below 500 meters was used.

**Table 2: Summary of Data Sources**

Data	Source	Type	Extent
USGS Digital Elevation Model	Puget Sound Regional Synthesis Model	30 meter grid	Washington State
1990-2000 Land cover classification	Urban Ecology Research Laboratory	30 meter grid	Central Puget Sound
2002 Land cover classification	Urban Ecology Research Laboratory	30 meter grid	Puget Sound
U.S. Census Data 2000, 1990	Washington Geographic Data Alliance	Geolitics	Washington State
Shellfish Growing Area Classifications	Washington Department of Health	Table	Puget Sound
Water quality station locations	Washington Department of Health	Point file	Puget Sound
Fecal Pollution Index	Washington Department of Health	Excel file	Puget Sound
Water quality monitoring data, 1988- 2002	Washington Department of Health	Excel table	Puget Sound
TIGER Transportation Data 2000	Puget Sound Regional Council	Vector File	Washington State
Clallam County Land Use Data	Clallam County Planning Department	Vector File	Clallam County
Clallam County Tax Assessors Data	Clallam County Planning Department	Vector File	Clallam County
Jefferson County Land Use Data	Jefferson County Planning Department	Vector File	East Jefferson County
Jefferson County Tax Assessors Data	Jefferson County Planning Department	Vector File	East Jefferson County
Kitsap County Land Use Data	Kitsap County Planning Department	Vector File	Kitsap County
Kitsap County Tax Assessors Data	Kitsap County Planning Department	Vector File	Kitsap County
Thurston County Land Use Data	Thurston County Planning Department	Vector File	Thurston County
Thurston County Tax Assessors Data	Thurston County Planning Department	Vector File	Thurston County
Pierce County Land Use Data	Pierce County Planning Department	Vector Data	Pierce County
Pierce County Tax Assessor Data	Pierce County Planning Department	Vector Data	Pierce County
King County Land Use Data	King County Planning Department	Vector Data	King County
King County Tax Assessors Data	King County Planning Department	Vector Data	King County
Snohomish County Land Use Data	Snohomish County Planning Department	Vector Data	Snohomish County
Snohomish County Tax Assessors Data	Snohomish County Planning Department	Vector Data	Snohomish County
Skagit County Land Use Data	Skagit County Planning Department	Vector Data	Skagit County
Skagit County Tax Assessors Data	Skagit County Planning Department	Vector Data	Skagit County
Whatcom County Land Use Data	Whatcom County Planning Department	Vector Data	Whatcom County
Whatcom County Tax Assessors Data	Whatcom County Planning Department	Vector Data	Whatcom County
Island County Land Use Data	Island County Planning Department	Vector Data	Island County
Island County Tax Assessors Data	Island County Planning Department	Vector Data	Island County
San Juan County Land Use Data	San Juan County Planning Department	Vector Data	San Juan County
San Juan County Tax Assessors Data	San Juan County Planning Department	Vector Data	San Juan County

**Table 3: Complete List of Land Use and Landscape Metrics**

<b>Intensity Metrics</b>	<b>Composition Metrics</b>	<b>Configuration Metrics</b>
Residential Road Length	Total Impervious Surface	Aggregation Index
Major Road Length	Percent Land Cover	– Forest
Total Road Density	Change in Percent Land Cover	– Mixed Urban
Population Density per Basin	Change in Percent	– Paved
Population Density per Paved	Paved Urban	– Grass, Shrub, Crop
	Mixed Urban	Percent Land Adjacency
		- Forest
		- Mixed Urban
		- Paved Urban

**Table 4. Landscape Metrics Definitions and Equations**

<b>Landscape Metrics</b>	<b>Equations</b>
<p><i>Percentage Land</i></p> <p>Sum of the area of all patches of the corresponding patch type divided by total landscape area.</p>	$pLand = \frac{\sum_{j=1}^n a_{ij}}{A}$
<p><i>Road Density</i></p> <p>Kilometers of road length per km<sup>2</sup> of land area.</p>	$rDensity = \frac{\sum_{j=1}^n l_j}{A}$
<p><i>Population Density</i></p> <p>Number of people per km<sup>2</sup> of land area.</p>	$pDensity = \frac{\# \text{ People}}{A}$
<p><i>Mean Patch Size</i></p> <p>Sum of the areas of all patches divided by the number of patches.</p>	$MPS = \frac{\sum_{j=1}^n a_{ij}}{ni}$
<p><i>Percent Like Adjacency</i></p> <p>Equals the sum of the number of like adjacencies for each patch type, divided by the total number of cell adjacencies in the landscape; multiplied by 100.</p>	$PLADJ = (100) \left( \frac{g_{ii}}{\sum_{k=1}^m g_{ik}} \right)$
<p><i>Aggregation Index</i></p> <p>Equals the number of like adjacencies involving the corresponding class, divided by the maximum possible number of like adjacencies involving the corresponding class; multiplied by 100.</p>	$AI = (100) \left[ \frac{g_{ii}}{\max \rightarrow g_{ii}} \right]$
<p><i>Contagion</i></p> <p>Probability of two cells of type I and j to be adjacent where m is the number of land cover types, <math>P_{ij}</math> is the proportion of cells in land cover i adjacent to cells of type j and <math>2 \ln(m)</math> is the maximum when all possible adjacencies of class i and j occur with equal probability.</p>	$C = \frac{2 \ln(m) + \sum_{i=1}^m \sum_{j=1}^m P_{ij} \ln P_{ij}}{2 \ln(m)}$

**Table 5: Definitions of Land Cover Classes**

<b>1991- 1999 Land Cover Classes</b>	<b>Description</b>
Paved Urban >75%	>75% impervious
Mixed Urban 15-75%	15-75% impervious
Forest	Coniferous and deciduous forest
Grass Shrub Crops	Agricultural land, fields, orchards
Bare Soil	Exposed soils
Clear Cut	Forest practice areas
Water	Open water, lakes, streams

<b>2002 Land Cover Classes</b>	<b>Description</b>
Paved Urban >75%	>75% impervious
Mixed Urban 15-75%	15-75% impervious
Forest	Coniferous and deciduous forest
Grass Shrub Crops	Agricultural land, fields, orchards
Dry Grass	Natural, non-irrigated grasses
Bare Soil	Exposed soils
Clear Cut	Forest practice areas
Water	Open water, lakes, streams
Rock, Snow, Ice	Reflective pixels above 1000 meters
Shoreline	
Wetlands	National Wetland Inventory land (NWI)
Steep Slope Mask	Steep slopes over 30% grade

**Table 6: Definitions of Land Use Classes**

We developed a combined system of land use codes for the purpose of analyzing land-use/land-cover relationships across 11 counties. As each county has their own set of codes, we needed a systematic way to compare land uses across 11 counties.

<b>Puget Sound Aggregated Land Use Classes</b>	<b>Description</b>	<b>Land Use Detail Description</b>
Single Family Residential	SFR	Includes single family residential, bed & breakfasts, mobile home parks
Multi-Family Residential	MFR	Duplex, triplex, apartment buildings
Mixed Use	Mixed Use	Residential with institutional lodging, Residential with motels/hotels, Residential with other Commercial
	Miscellaneous Development	Anything that does not fit into the rest of the classes
Commercial	Commercial	Hotels, service, retail, sales, trade
	Heavy Commercial	Motor vehicle sales/equipment, regional shopping center, fueling stations, scrap & waste material
	Built Recreation	Bowling alleys, pools, stadiums, fairgrounds, race tracks, amphitheaters, motion picture theaters, recreational centers
	Fisheries	Shellfish fisheries, hatcheries, fish related activities
Agriculture	Agriculture	Farms - poultry, dairy, crops, and livestock
Industrial	Industrial	Light manufacturing including food/paper processing, all terminal - air/marine/train, warehouses, landfills, treatment plants, military bases/installations
	Heavy Industrial	Mining activities, heavy manufacturing
	Heavy Use Transport	Highways, expressways, linear railroad lines
Office	Office	Service offices without retail - includes doctor and real-estate; military admin/logistics centers.
	Heavy Use Office	Microsoft or downtown Seattle concentration of banks, financial centers etc.
Institutional	Institutional	Schools, churches, government, hospitals, museums, etc.
Parking	Parking	Parking lots
Open Space	Vacant	Any undeveloped land
	Protected Forest	Protected/undevelopable land, open space, parks, wildlife refuge, greenbelts, non-commercial forest
	Unprotected Forest	Timberland and any forest land for commercial purposes.
	Non-built Recreation	Space for recreational activities including golf, playgrounds, beaches, resorts
Water	Water	Water areas, such as lakes.
Tribal	Tribal Lands	All Indian reservation land includes all activities - commercial, industrial, residential, etc.
Transport	Transportation	Linear roads, arterials, streets, alleys, communication exchanges, utilities, transmission right of way.

**Table 7: Definitions of Selected U.S. Census TIGER Road Classes**

The road classification system was adapted from U.S. Census TIGER road classification system. The TIGER database contains integrated information for geographic entities, roads, landmarks and place names. The road classifications used in our project are listed by class type and description.

Road Variable	TIGER Class	Definition
Major Roads	A1, A2, A3	Interstate highways, primary, secondary roads, hard surfaces
Local Roads	A4	Local traffic, residential, single lane in each direction
Service Roads	A51	Vehicular trails, fire roads, logging roads
4 Wheel Drive Roads	A74	Service roads, logging access roads, farms, park roads

**Table 8. Water Quality Metrics**

Water Metrics for Each Watershed	Equations
<p><i>Fecal Coliform Mean</i></p> <p>Mean fecal coliform bacteria from measurements taken within each basin</p>	$FCMean = \frac{\sum_{j=1}^n FC_j}{n}$
<p><i>Fecal Coliform Geometric Mean</i></p> <p>The nth root of the product of the fecal coliform measurements, where n represents the number of measurements.</p>	$FCgeomean = \sqrt[n]{\prod_{j=1}^n FC_j}$
<p><i>Fecal Coliform Exceedance Rate</i></p> <p>Number of measurements that exceeded 43 fecal coliform divided by the total number of measurements</p>	$Exc = \frac{\sum_{j=1}^n (FC \geq 43)_j}{n}$
<p><i>Fecal Coliform 90<sup>th</sup> Percentile</i></p> <p>The value above which 10 percent of the observed fecal coliform measurements fall and below which 90 percent of the observed measurements of fecal coliform fall.</p>	<p>FC 90<sup>th</sup> Percentile</p>
<p><i>Fecal Coliform Pollution Index(FPI)</i></p> <p>The Fecal Pollution Index is a weighted ranking tool calculated by the Department of Health for evaluating the impact of fecal pollution at the level of the sampling station, growing area and region. At each scale, the index categorizes samples as good (90<sup>th</sup> percentile below 30 MPN), fair (90<sup>th</sup> percentile between 30 and 43 MPN) or bad (estimated 90<sup>th</sup> percentile above 43 MPN).</p>	<p>Fecal Coliform Pollution Index Calculation:</p> <p>Sampling Station: The proportion of 90<sup>th</sup> percentiles in each category (good, fair, bad) multiplied by a weighting factor of 1, 2, 3 respectively and summed.</p> <p>Growing Area or Region: The proportion of 90<sup>th</sup> percentiles in each category in a growing area or region multiplied by the weighting factor and summed.</p>

**Table 9. 2002 Land Cover Classification: Percentages by Class for 18 Study Sites**

Basin	Percent Total Urban	Percent Mixed Urban	Percent Paved Urban	Percent Bare Soil	Percent Dry Grass	Percent Clear Cuts	Percent Grass, Shrub, Crop
Burley Lagoon	12.8%	10.6%	2.1%	0.3%	3.8%	0.0%	8.8%
Dabob Bay	1.4%	1.0%	0.3%	0.0%	0.8%	0.5%	4.5%
Dyes Inlet	20.9%	13.6%	7.3%	0.3%	2.5%	0.2%	5.4%
Eld Inlet	5.7%	4.3%	1.5%	0.3%	2.4%	0.0%	10.3%
Filucy Bay	4.3%	3.6%	0.7%	0.1%	5.8%	0.0%	10.3%
Henderson Inlet	26.8%	16.4%	10.3%	0.8%	7.3%	0.1%	9.5%
Kilisut Harbor	7.7%	5.6%	2.1%	0.1%	5.6%	0.0%	4.3%
North Bay	3.6%	3.1%	0.5%	0.1%	1.6%	0.3%	4.4%
Oakland Bay	6.0%	4.0%	2.0%	0.5%	3.8%	0.3%	10.8%
Quartermaster Harbor	5.1%	4.4%	0.7%	0.1%	3.8%	0.0%	9.7%
Rocky Bay	4.7%	4.3%	0.4%	0.1%	1.3%	0.0%	5.1%
Totten Inlet	4.1%	2.9%	1.2%	0.1%	2.0%	0.5%	10.1%
Budd Inlet	10.5%	6.8%	3.7%	0.3%	4.8%	1.7%	9.3%
Dungeness Bay	2.2%	1.5%	0.7%	0.2%	2.8%	0.3%	3.3%
Nisqually Reach	4.2%	2.9%	1.3%	0.2%	4.3%	1.8%	6.6%
Port Townsend	7.2%	5.3%	1.9%	0.1%	6.0%	0.1%	10.9%
Samish Bay	5.0%	4.0%	1.1%	0.9%	3.1%	0.1%	21.4%
Sequim Bay	5.5%	3.9%	1.6%	0.2%	3.1%	0.9%	6.7%

Basin	Percent Forest	Percent Water	Percent Snow, Rock, Ice	Percent Wetlands	Percent Shoreline	Percent Steep Slope Mask
Burley Lagoon	73.4%	0.2%	0.0%	0.1%	0.6%	0.0%
Dabob Bay	91.7%	0.3%	0.0%	0.1%	0.6%	0.1%
Dyes Inlet	68.2%	1.8%	0.0%	0.3%	0.2%	0.1%
Eld Inlet	79.9%	0.4%	0.0%	0.7%	0.2%	0.2%
Filucy Bay	76.9%	0.3%	0.0%	1.7%	0.5%	0.1%
Henderson Inlet	49.6%	3.3%	0.0%	2.3%	0.1%	0.3%
Kilisut Harbor	78.1%	0.3%	0.0%	0.4%	3.4%	0.2%
North Bay	84.6%	3.5%	0.0%	1.2%	0.2%	0.3%
Oakland Bay	73.7%	1.9%	0.0%	2.6%	0.0%	0.3%
Quartermaster Harbor	78.2%	1.6%	0.0%	0.0%	1.6%	0.0%
Rocky Bay	85.5%	1.3%	0.0%	1.6%	0.3%	0.2%
Totten Inlet	79.3%	2.6%	0.0%	0.6%	0.1%	0.6%
Budd Inlet	70.5%	1.6%	0.0%	1.1%	0.0%	0.2%
Dungeness Bay	69.3%	0.1%	18.7%	0.0%	0.0%	3.0%
Nisqually Reach	77.2%	1.6%	3.2%	0.7%	0.0%	0.3%
Port Townsend	74.1%	0.7%	0.0%	0.3%	0.6%	0.2%
Samish Bay	67.4%	1.1%	0.0%	0.7%	0.1%	0.1%
Sequim Bay	83.0%	0.3%	0.0%	0.0%	0.1%	0.1%

**Table 10 (a). Land Use Codes: Percentages by Class for 18 Study Sites:** Land use codes from 11 counties were collected and calibrated to create a condensed 14 categories. Areas with no data represent areas where information was not available.

Basin	Total Land Area Classified by Land Use (km <sup>2</sup> )	Percent Single Family Residential	Percent Multi Family Residential	Percent Mixed Use	Percent Commercial	Percent Agriculture	Percent Industrial
Burley Lagoon	41.75020709	9.0%	48.3%	0.5%	0.1%	0.3%	1.2%
Dabob Bay	59.18969493	2.5%	9.3%	0.0%	1.4%	0.1%	0.0%
Dyes Inlet	102.5879436	10.6%	27.1%	1.3%	0.5%	1.9%	1.0%
Eld Inlet	88.87024621	0.0%	0.0%	3.0%	43.1%	4.5%	5.0%
Filucy Bay	13.43491551	5.0%	32.1%	0.0%	0.0%	0.0%	11.0%
Henderson Inlet	120.1919344	0.0%	3.3%	4.4%	12.4%	7.8%	4.7%
Kilisut Harbor	14.20918201	33.8%	11.9%	0.0%	42.6%	0.0%	0.0%
North Bay	na	na	na	na	na	na	na
Oakland Bay	na	na	na	na	na	na	na
Quartermaster Harbor	44.19721526	5.1%	28.2%	0.1%	0.0%	0.3%	0.0%
Rocky Bay	51.83014779	4.6%	19.5%	0.3%	0.0%	0.0%	0.2%
Totten Inlet	na	na	na	na	na	na	na
Budd Inlet	544.3974922	0.0%	1.0%	2.8%	39.0%	3.9%	6.2%
Dungeness Bay	527.5468124	4.4%	4.4%	0.0%	2.3%	0.2%	2.3%
Nisqually Reach	na	na	na	na	na	na	na
Port Townsend	119.0570878	14.1%	13.6%	0.2%	7.4%	0.3%	0.5%
Samish Bay	376.8195199	2.2%	14.6%	0.2%	0.0%	0.4%	29.4%
Sequim Bay	124.3066175	11.9%	11.0%	0.1%	8.6%	0.3%	4.5%

**Table 10 (b). Land Use Codes: Percentages by Class for 18 Study Sites, continued**

Basin	Percent Office	Percent Institutional	Percent Parking	Percent Open Space	Percent Water	Percent Tribal	Percent Transport	Percent Other
Burley Lagoon	1.7%	0.1%	0.7%	1.8%	35.8%	0.2%	0.0%	0.4%
Dabob Bay	0.0%	0.0%	0.0%	0.0%	86.7%	0.0%	0.0%	0.0%
Dyes Inlet	1.1%	0.4%	8.9%	0.9%	45.7%	0.1%	0.0%	0.5%
Eld Inlet	18.5%	25.0%	0.3%	0.1%	0.0%	0.2%	0.1%	0.0%
Filucy Bay	0.0%	0.0%	0.2%	0.0%	51.6%	0.0%	0.0%	0.0%
Henderson Inlet	23.3%	31.6%	6.2%	2.3%	0.0%	2.9%	1.2%	0.0%
Kilisut Harbor	0.0%	0.0%	0.0%	0.0%	11.6%	0.0%	0.0%	0.0%
North Bay	na	na	na	na	na	na	na	na
Oakland Bay	na	na	na	na	na	na	na	na
Quartermaster Harbor	1.0%	0.1%	1.6%	0.0%	58.6%	0.0%	0.0%	5.0%
Rocky Bay	0.1%	0.0%	0.1%	0.3%	73.2%	0.1%	0.0%	1.6%
Totten Inlet	na	na	na	na	na	na	na	na
Budd Inlet	12.2%	15.8%	1.7%	0.9%	14.7%	1.2%	0.5%	0.0%
Dungeness Bay	0.1%	0.0%	0.0%	0.0%	85.6%	0.1%	0.1%	0.4%
Nisqually Reach	na	na	na	na	na	na	na	na
Port Townsend	0.1%	0.1%	0.7%	0.0%	62.9%	0.0%	0.0%	0.2%
Samish Bay	0.8%	0.0%	0.3%	0.0%	49.8%	2.2%	0.0%	0.2%
Sequim Bay	0.3%	0.0%	0.0%	0.0%	61.0%	0.1%	0.1%	1.9%

**Table 11. 2000 Road Density: Total Road Density and TIGER Road Lengths**

Basin	Total Road Length (km)	Major & Local Road Length (km)	Major Road Density (km/km <sup>2</sup> )	Local Road Density (km/km <sup>2</sup> )	Major & Local Road Density (km/km <sup>2</sup> )	4WD Road Density (km/km <sup>2</sup> )	Logging Road Density (km/km <sup>2</sup> )	Total Road Density (km/km <sup>2</sup> )
Burley Lagoon	150.36	148.67	0.38	3.19	3.56	0.00	0.04	3.60
Dabob Bay	86.26	86.26	0.05	1.41	1.46	0.00	0.00	1.46
Dyes Inlet	399.26	399.26	0.25	3.64	3.89	0.00	0.00	3.89
Eld Inlet	205.34	194.03	0.16	2.02	2.18	0.00	0.13	2.30
Filucy Bay	42.26	42.13	0.00	3.13	3.13	0.00	0.01	3.14
Henderson Inlet	504.48	493.80	0.09	4.01	4.10	0.00	0.09	4.19
Kilisut Harbor	48.49	48.49	0.62	2.77	3.39	0.00	0.00	3.39
North Bay	271.64	266.37	0.15	1.75	1.89	0.02	0.02	1.93
Oakland Bay	802.98	798.97	0.10	2.46	2.57	0.00	0.01	2.58
Quartermaster Harbor	146.49	146.49	0.00	3.31	3.31	0.00	0.00	3.31
Rocky Bay	113.62	112.87	0.11	2.04	2.16	0.00	0.01	2.17
Totten Inlet	210.98	206.03	0.15	1.85	2.01	0.03	0.02	2.06
Budd Inlet	1681.32	1592.83	0.05	2.87	2.93	0.06	0.10	3.09
Dungeness Bay	333.16	332.69	0.02	0.62	0.63	0.00	0.00	0.63
Nisqually Reach	3807.62	3633.91	0.09	1.67	1.76	0.03	0.05	1.84
Port Townsend	359.84	358.82	0.20	2.81	3.01	0.00	0.01	3.02
Samish Bay	616.38	591.81	0.17	1.39	1.56	0.05	0.01	1.63
Sequim Bay	256.65	253.42	0.15	1.85	1.99	0.00	0.03	2.02

**Table 12. Population Density from 2000 U.S. Census Block Groups**

Basin	Population	Population Density (pop/km <sup>2</sup> )	Population per Total Roads (pop/km)	Population per Total Paved Area (pop/km <sup>2</sup> )	Major Roads per Population (km/pop)
Burley Lagoon	8514	204.1	56.62	1184.99	0.02
Dabob Bay	219	3.7	2.54	236.01	0.39
Dyes Inlet	42012	409.5	105.22	1561.14	0.01
Eld Inlet	8848	99.3	43.09	1438.43	0.02
Filucy Bay	1469	109.3	34.76	1952.46	0.03
Henderson Inlet	71867	597.1	142.46	2030.92	0.01
Kilisut Harbor	954	63.0	19.68	623.36	0.05
North Bay	4963	35.3	18.27	652.58	0.05
Oakland Bay	24129	77.6	30.05	911.15	0.03
Quartermaster Harbor	4176	94.5	28.51	1260.17	0.04
Rocky Bay	3612	69.0	31.79	1008.95	0.03
Totten Inlet	4850	47.3	22.99	1058.68	0.04
Budd Inlet	94640	173.8	56.29	1278.90	0.02
Dungeness Bay	13205	25.0	39.63	248.91	0.03
Nisqually Reach	118521	57.3	31.13	638.19	0.03
Port Townsend	8450	71.6	23.48	644.19	0.04
Samish Bay	11708	30.9	18.99	561.17	0.05
Sequim Bay	6791	53.4	26.46	661.66	0.04

**Table 13. Forest Landscape Metrics**

Basin	Forest Percent Land	Forest Percent Like Adjacencies	Forest Aggregation Index
Burley Lagoon	73.42 %	87.22	87.70
Dabob Bay	91.74 %	95.89	96.28
Dyes Inlet	68.24 %	88.02	88.34
Eld Inlet	79.88 %	91.49	91.81
Filucy Bay	76.86 %	89.27	90.12
Henderson Inlet	49.59 %	81.25	81.57
Kilisut Harbor	78.81 %	91.01	91.84
North Bay	84.59 %	94.06	94.32
Oakland Bay	73.72 %	90.36	90.54
Quartermaster Harbor	78.15 %	91.02	91.49
Rocky Bay	85.49 %	92.96	93.38
Totten Inlet	79.32 %	92.19	92.50
Budd Inlet	67.30 %	90.73	90.87
Dungeness Bay	69.26 %	93.17	93.31
Nisqually Reach	70.69 %	94.11	94.19
Port Townsend	73.98 %	91.87	92.17
Samish Bay	67.30 %	91.48	91.66
Sequim Bay	83.01 %	93.83	94.11

**Table 14. Paved Urban Landscape Metrics**

Basin	Percent Paved Urban	Percent Paved Like Adjacencies	Paved Aggregation Index
Burley Lagoon	2.13 %	40.84	42.19
Dabob Bay	0.34 %	32.96	35.34
Dyes Inlet	7.32 %	63.90	64.61
Eld Inlet	1.47 %	45.36	46.59
Filucy Bay	0.70 %	21.90	24.34
Henderson Inlet	10.31 %	64.57	65.12
Kilisut Harbor	1.87 %	38.18	40.57
North Bay	0.49 %	37.55	38.96
Oakland Bay	2.01 %	61.23	61.97
Quartermaster Harbor	0.70 %	38.37	40.62
Rocky Bay	0.38 %	26.48	28.43
Totten Inlet	1.17 %	43.91	45.15
Budd Inlet	3.55 %	65.14	65.59
Dungeness Bay	0.73 %	52.31	53.12
Nisqually Reach	1.22 %	56.36	56.69
Port Townsend	1.92 %	49.71	50.71
Samish Bay	1.08 %	52.01	52.79
Sequim Bay	1.58 %	58.84	60.12

**Table 15. Mixed Urban Landscape Metrics**

Basin	Percent Mixed Urban Land	Mixed Urban Percent Like Adjacencies	Mixed Urban Aggregation Index
Burley Lagoon	10.64 %	40.57	41.16
Dabob Bay	1.02 %	28.32	29.46
Dyes Inlet	13.62 %	46.40	46.78
Eld Inlet	4.27 %	34.70	35.24
Filucy Bay	3.63 %	26.94	28.16
Henderson Inlet	16.44 %	51.89	52.25
Kilisut Harbor	5.54 %	28.52	29.53
North Bay	3.15 %	33.90	34.40
Oakland Bay	4.01 %	37.46	37.79
Quartermaster Harbor	4.40 %	29.95	30.61
Rocky Bay	4.31 %	34.44	35.15
Totten Inlet	2.95 %	31.18	31.73
Budd Inlet	6.54 %	47.63	47.87
Dungeness Bay	1.49 %	35.55	35.93
Nisqually Reach	2.70 %	36.23	36.38
Port Townsend	5.31 %	42.94	43.46
Samish Bay	3.96 %	38.07	38.37
Sequim Bay	3.90 %	38.16	38.68

**Table 16. Fecal Coliform Descriptive Statistics—All Data from 1998- 2002**

Basin	# FC Samples	FC Minimum	FC Maximum	FC Mean	FC Geometric Mean	FC Standard Deviation	FC Median	# of Samples Exceeding 43 Organisms	Exceed-ence Rate	90th Percentile
Burley Lagoon	1457.00	1.80	920.00	15.95	5.95	48.39	4.50	113.00	7.76%	33.00
Dabob Bay	582.00	1.80	23.00	2.36	2.07	2.06	1.80	na	na	2.65
Dyes Inlet	1252.00	1.80	1600.00	11.77	4.41	51.37	2.00	64.00	5.11%	23.00
Eld Inlet	2905.00	1.80	920.00	9.15	3.78	29.41	2.00	114.00	3.92%	17.00
Filucy Bay	559.00	1.80	2400.00	35.46	5.29	177.21	2.00	53.00	9.48%	33.00
Henderson Inlet	3428.00	1.80	2400.00	15.69	5.77	62.19	4.50	236.00	6.88%	33.00
Kilisut Harbor	1788.00	1.70	350.00	2.91	2.01	13.17	1.80	10.00	0.56%	2.00
North Bay	1763.00	1.80	920.00	12.62	4.84	40.39	4.00	95.00	5.39%	23.00
Oakland Bay	2381.00	1.80	1600.00	13.91	4.81	54.07	4.00	147.00	6.17%	27.00
Quartermaster Hbr.	533.00	1.80	350.00	7.17	3.25	20.45	2.00	14.00	2.63%	15.18
Rocky Bay	883.00	1.80	1600.00	11.43	4.35	56.84	2.00	45.00	5.10%	23.00
Totten Inlet	2063.00	1.30	170.00	4.27	2.68	9.14	1.80	19.00	0.92%	7.80
Budd Inlet	41.00	1.80	49.00	8.69	4.45	12.34	2.00	2.00	4.88%	32.60
Dungeness Bay	974.00	1.70	540.00	15.72	6.02	33.16	4.50	98.00	10.06%	46.00
Nisqually Reach	3092.00	1.80	540.00	10.85	4.34	26.27	2.00	182.00	5.89%	25.24
Port Townsend	544.00	0.17	540.00	5.23	2.48	26.34	1.80	6.00	1.10%	6.80
Samish Bay	2107.00	1.80	540.00	10.87	3.84	31.12	2.00	120.00	5.70%	23.00
Sequim Bay	2112.00	1.70	240.00	3.39	2.26	8.95	1.80	15.00	0.71%	4.50

**Table 17. Fecal Coliform Descriptive Statistics—Seasonal Data from 1998-2002**

Basin	# FC Samples	FC Minimum	FC Maximum	FC Mean	FC Geometric Mean	FC Standard Deviation	FC Median	# of Samples Exceeding 43 Organisms	Exceedence Rate	90th Percentile
Burley Lagoon	624.00	1.80	920.00	6.17	6.17	56.88	4.50	57.00	9.1%	33.00
Dabob Bay	18.00	1.80	17.00	2.96	2.96	4.44	1.80	na	na	13.40
Dyes Inlet	432.00	1.80	1600.00	4.42	4.42	79.12	2.53	20.00	4.6%	23.00
Eld Inlet	1080.00	1.80	920.00	4.16	4.16	40.10	2.00	44.00	4.1%	22.00
Filucy Bay	216.00	1.80	2400.00	4.89	4.89	202.63	2.00	22.00	10.2%	49.00
Henderson Inlet	1584.00	1.80	2400.00	5.40	5.40	70.99	4.50	97.00	6.1%	29.00
Kilisut Harbor	852.00	1.70	350.00	2.03	2.03	13.96	1.80	7.00	0.8%	2.00
North Bay	870.00	1.80	540.00	4.66	4.66	35.49	2.70	41.00	4.7%	23.00
Oakland Bay	1032.00	1.80	1600.00	4.93	4.93	63.25	4.00	65.00	6.3%	30.61
Quartermaster Hbr.	72.00	1.80	41.40	3.04	3.04	8.35	1.87	na	na	16.40
Rocky Bay	156.00	1.80	110.00	4.81	4.81	17.38	2.00	8.00	5.1%	31.60
Totten Inlet	456.00	1.80	130.00	2.65	2.65	9.70	1.80	3.00	0.7%	7.80
Budd Inlet	12.00	1.80	49.00	5.78	5.78	16.10	4.50	1.00	8.3%	44.20
Dungeness Bay	144.00	1.80	140.00	4.72	4.72	23.68	2.00	13.00	9.0%	33.00
Nisqually Reach	1332.00	1.80	540.00	4.43	4.43	28.35	2.00	87.00	6.5%	32.40
Port Townsend	12.00	1.70	4.50	1.84	1.84	0.81	1.70	na	na	3.66
Samish Bay	na	na	na	na	na	na	na	na	na	na
Sequim Bay	870.00	1.70	240.00	2.31	2.31	11.61	1.80	8.00	0.9%	4.50

**Table 18: Significant Correlations Between Landscape Variables and Fecal Coliform  
18 Basins (Cross-sectional data set)**

Landscape Variables	Combined Seasons (FC Geometric Mean)	Wet Season (FC Geometric Mean)	Dry Season (FC Geometric Mean)
	r	r	r
<u>Intensity Metrics</u>			
Population Density	0.48 <sup>*</sup>		0.62 <sup>**</sup>
Road Total Length			
Road Length per Person		0.49 <sup>*</sup>	
<u>Composition Metrics</u>			
% Impervious Surface	0.63 <sup>**</sup>	0.56 <sup>*</sup>	
% Urban Cover			0.57 <sup>*</sup>
% Mixed Urban Cover			0.62 <sup>**</sup>
% Forest Cover	-0.67 <sup>**</sup>		
<u>Configuration Metrics</u>			
AI Forest	-0.52 <sup>*</sup>		-0.65 <sup>**</sup>
PLADJ Forest	-0.50 <sup>*</sup>	0.48 <sup>*</sup>	-0.65 <sup>**</sup>
AI Mixed Urban	0.52 <sup>*</sup>		
PLADJ Mixed Urban	0.52 <sup>*</sup>		
<u>Local Metrics</u>			
% Paved Land (Local)		0.63 <sup>**</sup>	
% Forest (Local)	-0.49 <sup>*</sup>	-0.67 <sup>**</sup>	
(N=18)			
<sup>**</sup> $p < 0.01$			
<sup>*</sup> $p < 0.05$			

**Table 19: Significant Correlations Between Landscape Variables and Fecal Coliform  
12 Basins (Longitudinal data set)**

Landscape Variables	Combined Seasons (FC Geometric Mean)	Wet Season (FC Geometric Mean)	Dry Season (FC Geometric Mean)
	R	r	r
<u>Intensity Metrics</u>			
Population Density	0.72**		0.64*
Total Road Length		0.76*	
<u>Composition Metrics</u>			
% Impervious	0.62*		
% Urban	0.68*		0.62*
% Mixed Urban	0.70*		0.66*
% Forest	-0.70*	-0.63*	
<u>Configuration Metrics</u>			
AI Forest	-0.77**	-0.62*	-0.67*
PLADJ Forest	-0.75**	-0.60*	-0.67*
AI Paved		0.65*	
PLADJ Urban		0.66*	0.66*
AI Mixed Urban	0.77**	0.66*	0.65*
PLADJ Mixed Urban	0.77**	0.66*	
(N=12)			
** $p < 0.01$			
* $p < 0.05$			

**Table 20: Significant Models using Cross-sectional Sample Basins in Puget Sound (18)**

Response Variable: Geometric Mean Fecal Coliform (Combined Seasons)

Models	N	Independent	adj.R <sup>2</sup>	P
1.	18	% Forest Cover	0.41	0.003
2.	18	% Impervious	0.36	0.005
3.	18	AI Forest	0.23	0.026

Response Variable: Geometric Mean Fecal Coliform (Wet Season)

Models	N	Independent	adj.R <sup>2</sup>	P
1.	18	% Forest + Rod Den	0.47	0.003
2.	18	%Forest+Forest AI	0.44	0.005
3.	18	% Forest (Local)	0.44	0.003
4.	18	% Paved (Local)	0.40	0.005
5.	18	%Impervious	0.27	0.016

Response Variable: Geometric Mean Fecal Coliform (Dry Season)

Models	N	Independent	adj.R <sup>2</sup>	P
1.	18	Population Density	0.40	0.006
2.	18	Forest AI	0.39	0.003
3.	18	%Mixed Urban	0.38	0.006

**Table 21: Significant Models using Longitudinal Land cover subset (12)**

Response Variable: Geometric Mean Fecal Coliform (Combined Seasons)

Models	N	Independent	adj R <sup>2</sup>	P
1.	12	AI Mixed Urban	0.56	0.003
2.	12	AI Forest	0.55	0.003
3.	12	Pop Density	0.47	0.009
4.	12	% Forest	0.44	0.011
5.	12	% Impervious	0.33	0.030

Response Variable: Geometric Mean Fecal Coliform (Wet Season)

Models	N	Independent	R <sup>2</sup>	P
1.	12	Total Road Length	0.54	0.004
2.	12	AI Mixed Urban	0.37	0.021
3.	12	AI Urban	0.36	0.023
4.	12	% Forest	0.34	0.028

Response Variable: Geometric Mean Fecal Coliform (Dry Season)

Models	N	Independent	adj.R <sup>2</sup>	P
1.	12	AI Forest	0.40	0.016
2.	12	AI Mixed Urban	0.38	0.019
3.	12	% Mixed Urban	0.38	0.019
4.	12	Population Density	0.36	0.024

